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Effects of Charged Particles on Cascade Impactor Calibrations

Air Pollution Technology, Inc, San Diego, CA

Prepared for

Industrial Environmental Research Lab, Research Triangle Park, NC

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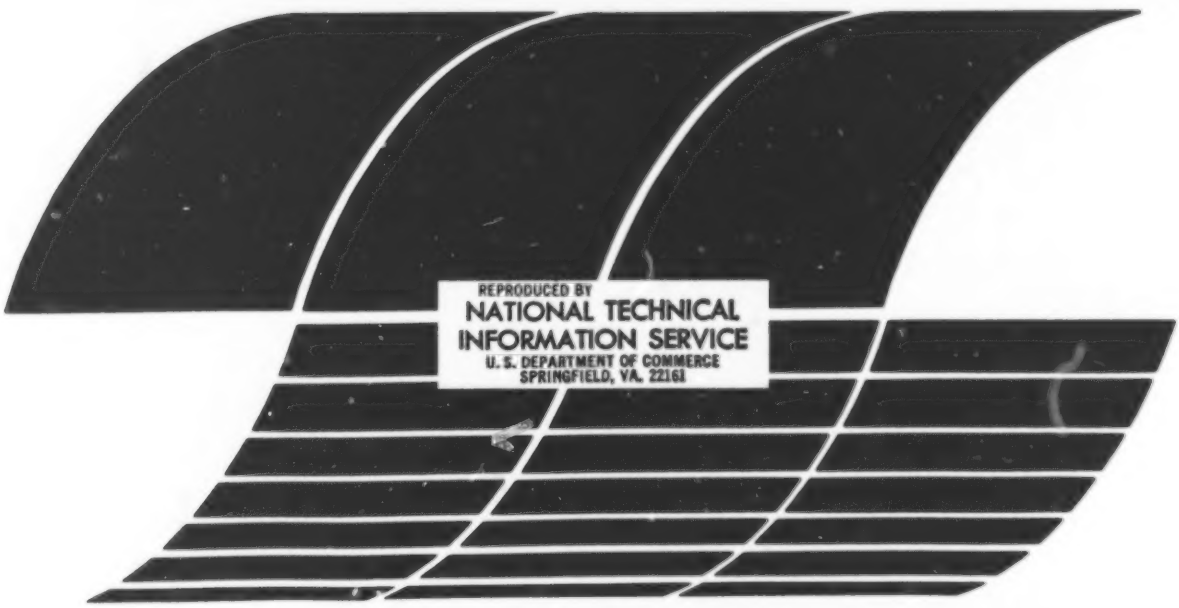

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Effects of Charged Particles on Cascade Impactor Calibrations

by

R. G. Patterson, Phillip Riersgard, and Seymour Calvert

Air Pollution Technology, Inc.
4901 Morena Boulevard, Suite 402
San Diego, California 92117

Contract No. 68-02-1496
ROAP 21ADL-004
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EPA Project Officer: Dale L. Harmon

Industrial Environmental Research Laboratory
Office of Energy, Minerals, and Industry
Research Triangle Park, NC 27711

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Washington, DC 20460

ABSTRACT

Collection characteristics were determined for charged and uncharged particles in cascade impactors. Collection efficiency on a wide variety of substrates was found to be greater for charged than uncharged particles.

This report was submitted in partial fulfillment of Contract No. 68-02-1496 by Air Pollution Technology, Inc. under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period January, 1977 to August, 1977.

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LIST OF SYMBOLS

A = area, cm^2

C' = Cunningham slip correction factor =

$$1 + \frac{2\ell}{d_p}\ 1/257 + 0.40 \exp\ (-1.10\ d_p/2\ell)$$

d_j = jet diameter, cm

d_p = particle physical diameter, μm

d_{pa} = aerodynamic particle diameter, μmA

d_{pc} = aerodynamic cut diameter

$d_{p_{50}}$ = cut diameter or diameter at which stage is 50% efficient

e = electronic charge value, 4.8×10^{-10} esu

E_o = applied electric field strength, kV/cm

I = current, amps

I_{SAT} = saturation current, amp

k = dielectric constant for particle

K_p = inertial impaction parameter, dimensionless

$K_{p_{50}}$ = inertial impaction cut parameter, K_p, at 50% efficiency

ℓ = mean free path of gas molecules, cm

n = number density of particles, #/cm^3

n_o = initial number density, #/cm^3

n_p = particle charge level, elementary units

n_s = saturation charge level, elementary units

ρ_p = particle density, g/cm^3

s = electrode spacing, cm

Q = volumetric flow rate, cm^3/s

q = charge on a particle, elementary units

μ_G = gas viscosity, poise, g/cm-s

μmA = μm $(g/cm^3)^{1/2}$

V = applied voltage

$\vec{v}$ = gas velocity, g cm/s

v_j = gas (particle) velocity through jet, cm/s

Z_p = electrical mobility of the particle, cm^2/volt-sec

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SECTION 1

INTRODUCTION

In the past few years considerable emphasis has been placed on determining the performance characteristics of particulate control devices. These investigations seek to establish the collection efficiency as a function of the particle size. To do this requires accurate determination of the size distribution of particles at the inlet and the outlet of the control device. Cascade impactors are routinely used in these investigations for establishing the size distribution of particles greater than 0.3 μmA diameter.

The particles which penetrate a particulate control device employing electrostatic forces for collection can have a higher level of charge than when they entered. Other investigators, Smith et al. (1975) and Brink et al. (1972), have found that the collection characteristics of cascade impactors can be altered when sampling charged particles.

This investigation was undertaken to evaluate the effect of charged particles on cascade impactor calibrations. The effect of particle charge on the collection efficiency can be expected to be a function of the charge level on the particle. Therefore a charge level was chosen for this study that is equivalent to that encountered on particles in electrostatic precipitators.

SECTION 2

CONCLUSIONS

The impaction collection efficiency was shown to be as much as 20% greater for charged particles than uncharged particles with certain substrates at a given value of the impaction parameter, K_p, using a University of Washington Impactor. Collection on greased substrates remained relatively unchanged.

The effect that charged particles will have on the particle size distribution measured with the cascade impactor can be determined from equation (5). This equation shows that the stage cut diameter, d_{pc}, is related to $K_{p_{50}}$ in the following way:

$$d_{pc}\ \text{charged} = d_{pc}\ \text{uncharged} \left[\frac{K_{p_{50}}\ \text{charged}}{K_{p_{50}}\ \text{uncharged}} \right]^{1/2}$$

The results of this investigation show that the impaction parameter, $K_{p_{50}}$, increases by 5 to 17% when collecting charged particles. The actual amount depends on the particle size and collection substrate used. For a 17% change in the impaction parameter, $K_{p_{50}}$, the change in the stage cut diameter, d_{pc}, is 8%.

SECTION 3

METHOD AND EXPERIMENTAL APPARATUS

Impactor calibrations were performed with charged and uncharged aerosols. The method for performing the calibration was adapted from the "Impactor Calibration Guidelines," Calvert et al. (1976). Figure 1 is a schematic of the impactor calibration system used.

The procedure involved generating the test aerosol and determining the collection efficiency as a function of the flow rate through the cascade impactor. The average charge level on the test aerosol was determined for the charged particle runs. Charge neutralization was used to assure that the uncharged particles were electrically neutral.

AEROSOL GENERATION

Monodisperse aerosols were produced using suspensions of polystyrene latex (PSL) microspheres. Particles of 0.5, 1.1, and 2.0 μm diameter were used for these calibrations. This is also the size range of most importance in fine particulate control device evaluation.

Useful suspensions of PSL were made by diluting small quantities of the original suspension with deionized water. The PSL is diluted to a concentration sufficient to minimize the occurrence of agglomeration. Dilutions of the stock 10% solutions of PSL can be estimated from a paper by Raabe; however, the amount of dilution necessary depends on the specific atomizer used. Concentrations of 0.01 to 0.2 weight percent for particles of 0.5 to 2.0 μm diameter were found to be compatible with the atomizer used.

Drops containing PSL particles were produced from suspensions with a Collison atomizer. The atomizer is a one-hole design operating at 260 kPa. Number concentrations and PSL

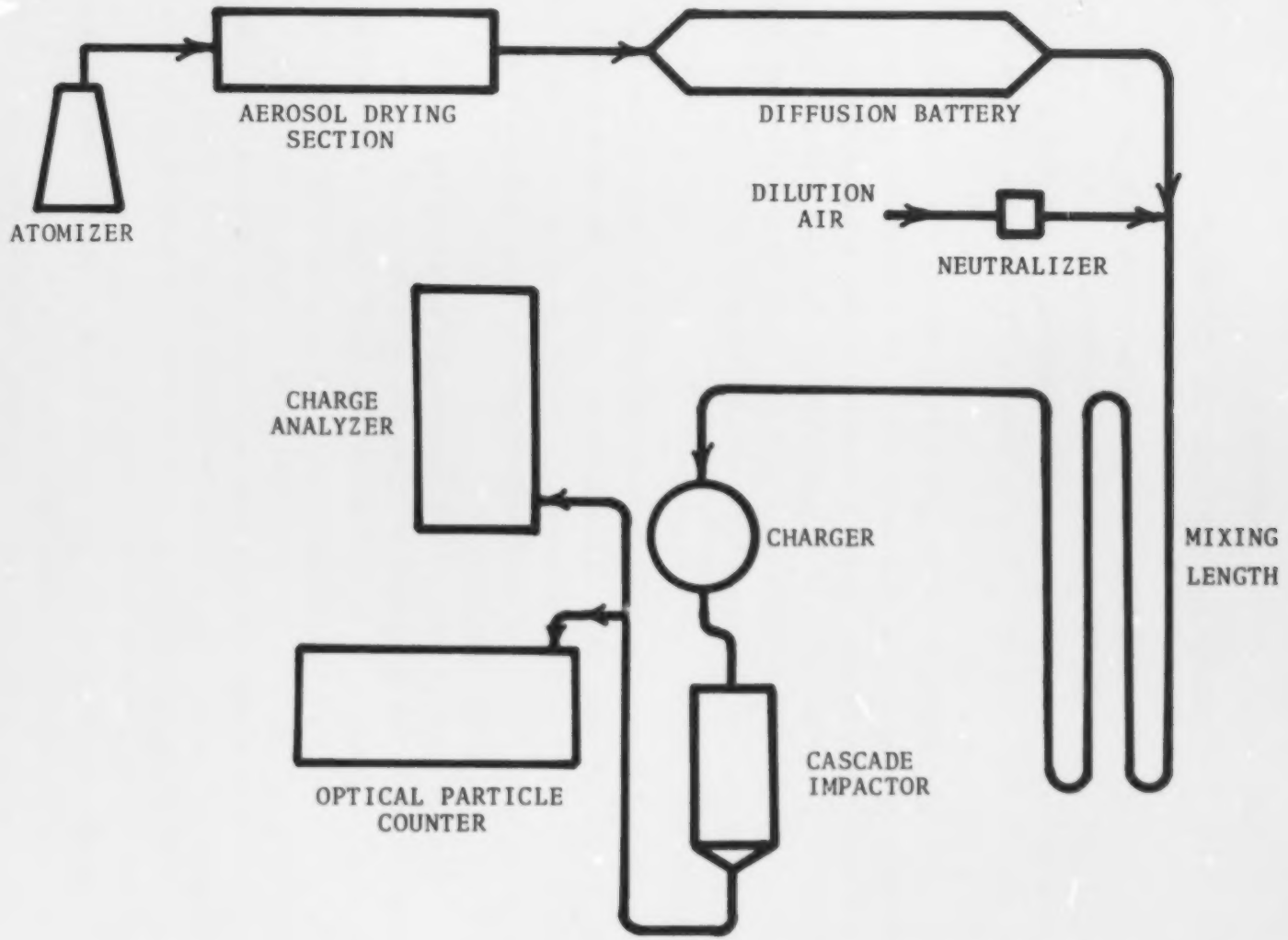

Figure 1. Impactor calibartion system.

size distributions were constant throughout a run.

The aerosol is dried by passing it through a 1.8 m section of a 3.6 cm diameter glass tube. The tube was mounted horizontally with a layer of silica gel (~1.5 cm deep) spread evenly along the bottom.

Submicron aerosols less than approximately 0.1 μm diameter were removed by passing the dried aerosol through a diffusion battery. Aerosol leaving the diffusion battery is mixed with ionized air (approximately 45 ℓ/min). The air is ionized with a 20 mCi, PO^{210} alpha emitter to reduce the excess charge on the aerosol to the Boltzman equilibrium level. The mixture passed through 6 m of 1.3 cm diameter glass tubing to provide adequate residence time for charge neutralization of the aerosol.

CHARGER

The effect of particle charge on the collection characteristics of cascade impactors was determined with particles having different levels of charge. For the purposes of this experiment the different charge levels were produced by charging three different size aerosols to their saturation charge level by ion bombardment. The charge levels are comparable to those obtained in conventional ESP's.

For a dielectric particle, such as PSL, field charging theory predicts the following saturation charge level, White (1963).

$$n_s = \left[1 + 2\left(\frac{k-1}{k+2}\right)\right]\frac{E_o\, d_p^{\,2}}{(1200)e} \times 10^{-8} \qquad (1)$$

$$n_s = 2.9 \times 10^{-2}\, E_o\, d_p^{\,2} \qquad (2)$$

(for PSL)

The saturation charge level is seen to be proportional to the applied field strength, E_o, and surface area of the particle ~$d_p^{\,2}$. Figure 2 gives the saturation charge level for field charging of particles in the size range of interest in this study.

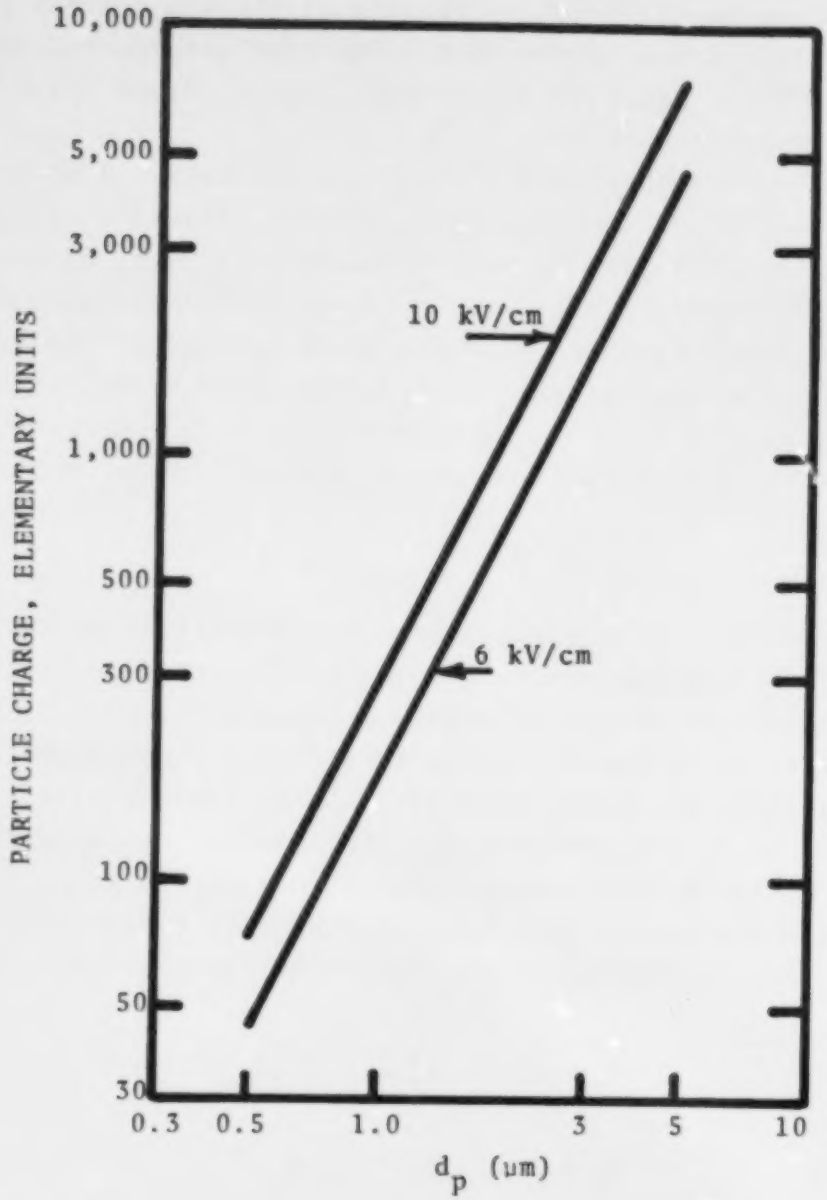

Figure 2. Saturation charge level on PSL aerosol (dielectric constant, k=2.55).

The field charger used is a modified version of the design cited by Langer et al. (1964). The device shown in Figure 3 consists of a small Plexiglas box with two inlets and one outlet. The aerosol enters the charging region through the lower glass tube. The outlet is a brass tube cut at a 45-degree angle to the center line of the pipe. The source of the ion flux is a small loop of platinum wire bent slightly and positioned so as to be equidistant from the outer edge of the tube. A DC power supply operating in the range of 0 → 12 kV was used for establishing the corona.

CASCADE IMPACTOR

A University of Washington Mark III source test cascade impactor was chosen for these tests. The impactor was calibrated with only one jet stage installed at a time according to the method of Calvert et al. (1976). In this manner, the difference in collection efficiency between charged and uncharged particles could be studied.

The inertial impaction parameter, K_p, is used to characterize the collection efficiency for a given impaction stage. The inertial impaction parameter is defined by:

$$K_p = \frac{d_p^2 \, C' \, \rho_p \, v_j}{9 \, \mu_G \, d_j} = \frac{d_{pa}^2 \, v_j}{9 \, \mu_G \, d_j} \times 10^{-8} \qquad (3)$$

Aerodynamic diameter is defined as:

$$d_{pa} = d_p \, (C' \, \rho_p)^{1/2} \times 10^4, \ \mu mA \qquad (4)$$

For the case where the stage is 50% efficient (i.e., the cut point) equation 2 becomes:

$$K_{p_{50}} = \frac{d_{p_{50}}^2 \, C' \, \rho_p \, v_j}{9 \, \mu_G \, d_j} = \frac{d_{pc}^2 \, v_j}{9 \, \mu_G \, d_j} \times 10^{-8} \qquad (5)$$

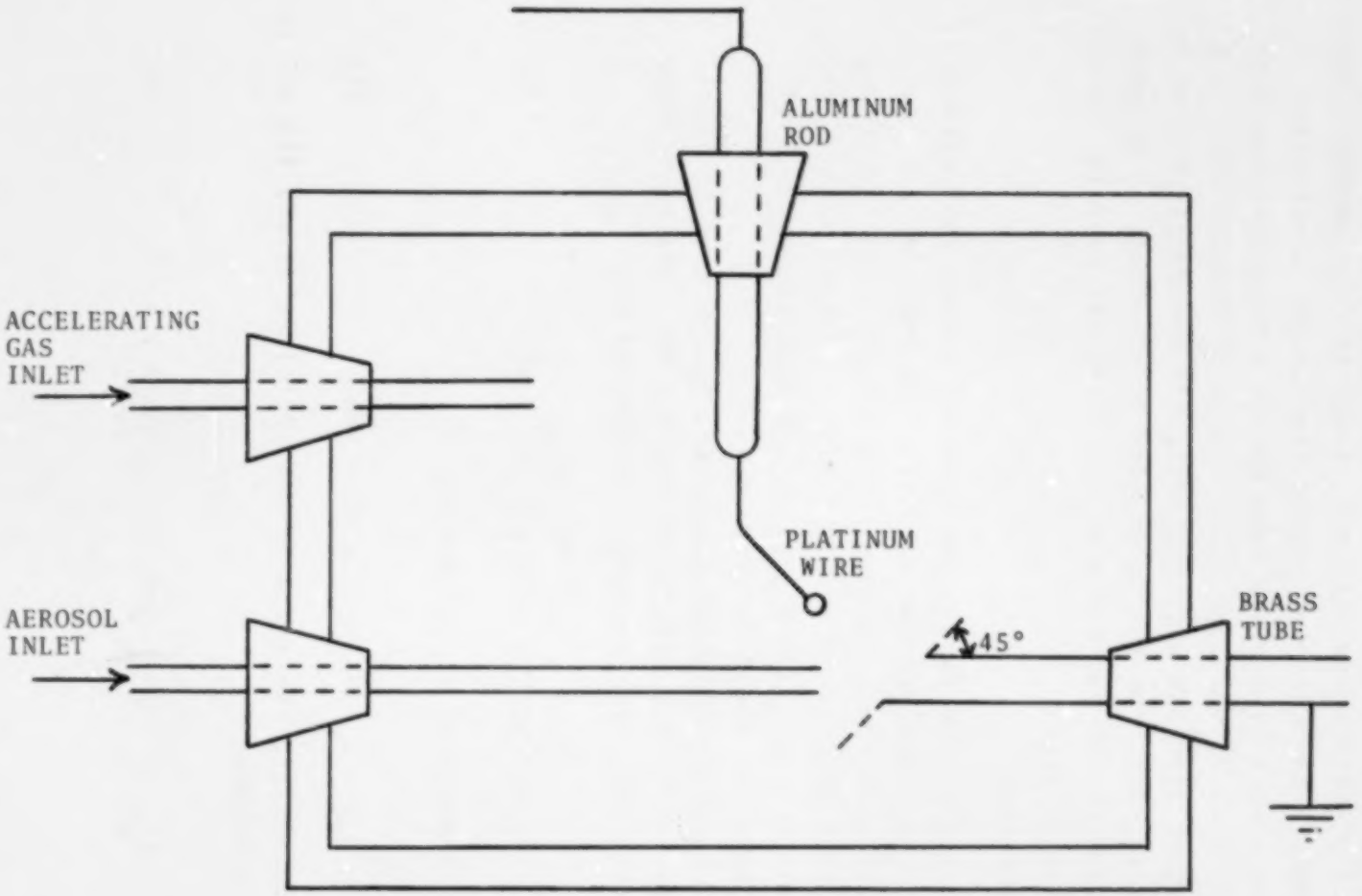

Figure 3. Aerosol charger.

Choosing the proper jet stage depends on the particle size being studied and knowledge of the volumetric flow rate usually encountered in the field. For field operations this impactor is normally operated in the range of $1.4 \times 10^{-2} \rightarrow 2.8 \times 10^{-2}$ m^3/min. With limits set on the desired volumetric flow rate, the following jet stages were chosen for the particle sizes used in this study:

Stage	d_p (μm)	Hole Dia (cm)	Number of Holes
4	2.0	0.079	90
5	1.0	0.051	110
6	0.5	0.034	110

A number of impaction substrates are used for determining size distributions in the field. The following substrates were chosen for study to give a representative sample of the conditions encountered:

1. Glass fiber filter on a metal impaction plate.
2. Greased metal impaction plate.
3. Ungreased metal impaction plate.
4. Greased aluminum foil on metal impaction plate.
5. Ungreased aluminum foil on metal impaction plate.
6. Teflon film on metal impaction plate.
7. Mylar film on metal impaction plate.

OPTICAL PARTICLE COUNTER

The number concentration of particles entering and leaving the cascade impactor was determined with a Climet CI 205 particle analyzer. The Climet device has the capability of counting all particles with diameters greater than a pre-set value (0.3, 0.5, 1.0, 3.0, 5.0, or 10.0 μm). Further discrimination is achieved by using a potentiometer to provide a continuous particle size selection over the range of 0.3 to 10.0 μm.

The particle counter is used within a selected band of particle diameters, centered about the known PSL diameter. This reduces the effect of spurious counts resulting from fine impurities and agglomerates. The particle count for the larger diameter

setting may be subtracted from that for the smaller diameter setting to determine the number concentration of particles within a desired size interval.

PARTICLE CHARGE ANALYZER

Two methods were tried for measuring the charge level of the particles. An imposed field analyzer was constructed to ascertain the electrical properties of the aerosol. A modified version of the design used by Hurd et al. (1962) is shown in Figure 4. The electrical mobility of the particles entering the device can be determined from the volt-ampere characteristics of the analyzer as shown in Figure 5. A particle entering the device will either be intercepted on the current collecting lower electrode or pass out of the system depending on the imposed electric field.

The trajectory of a particle entering the system is given by:

$$\frac{d\vec{r}}{dt} = Z_p \vec{E} + \vec{v} \tag{6}$$

and:

$$\vec{E} = -\frac{V}{s} \tag{7}$$

At low voltages, only a fraction of the particles are collected. Those entering above a critical value of x, x_o, are not collected while those entering below x_o will be collected. For a particular voltage, the current obtained from particles collected on the lower electrode is given by:

$$I = -\int_A nq\ bE_x\ da \tag{8}$$

$$= \int_A \frac{nq\ bV}{s}\ da$$

where A = area of collecting electrode
q = charge on a particle
n = number concentration of particles

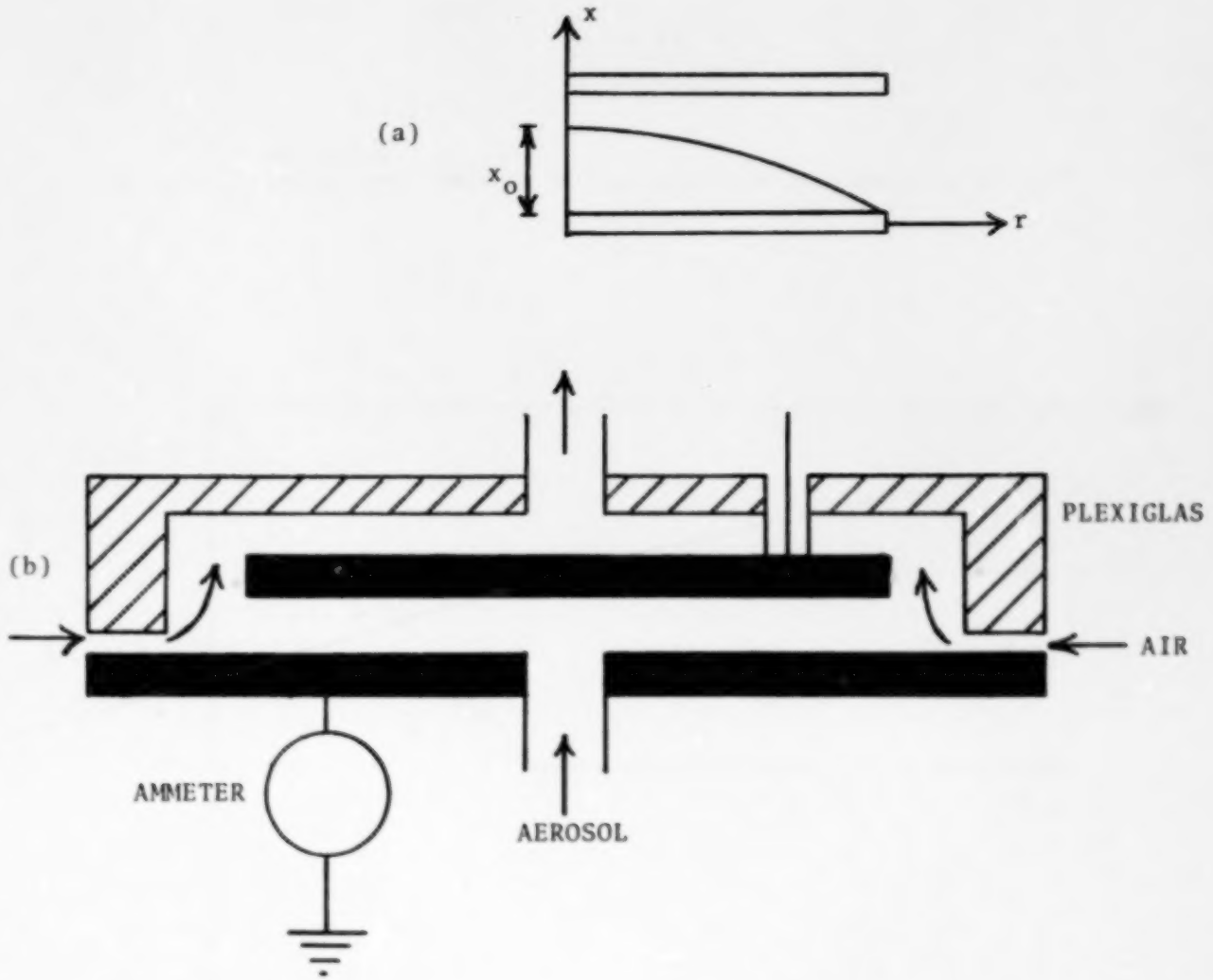

Figure 4. Radial flow aerosol charge analyzer.
(a) Particle trajectory
(b) Analyzer configuration

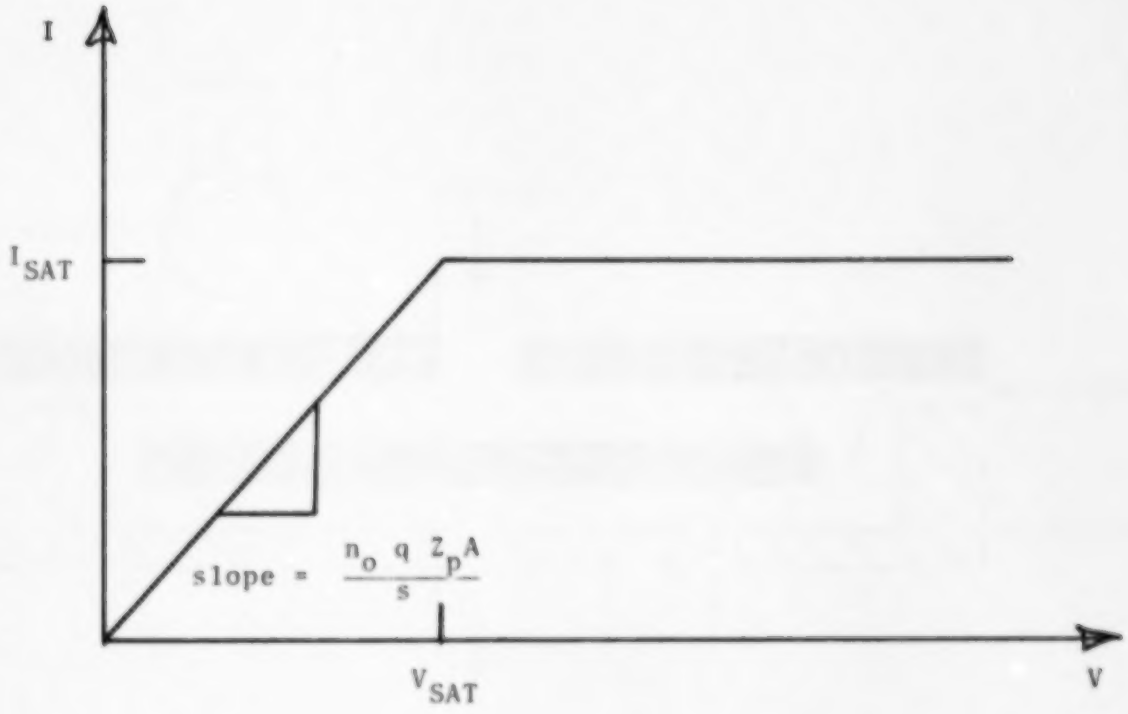

Figure 5. Ideal volt-ampere characteristic for aerosol charge analyzer.

The inlet concentration, n_o, is maintained in the region adjacent to the collecting electrode for every position, r. Applying this boundary condition to equation 8 results in:

$$I = \left[\frac{n_o q Z_p A}{s}\right] V \qquad (9)$$

When the voltage is raised such that all particles entering the system are collected on the lower plate the current becomes:

$$I = I_{SAT} = n_o q Q \qquad (10)$$

where, Q, is the volumetric rate of gas flow. Combining equations 9 and 10 results in the saturation voltage:

$$V_{SAT} = \frac{sQ}{Z_p A} \qquad (11)$$

from which the electrical mobility of the particle, Z_p, may be determined.

The charge level of the particle, n_p, is related to the electrical mobility of the particle, Z_p, by:

$$n_p = \frac{3\pi \mu d_p (300) Z_p}{eC} \times 10^{-4} \qquad (12)$$

The expected value of the saturation current, I_s, may be determined by assuming the particles attain the saturation charge level. Table 1 gives the expected value of the saturation current for particles charged in a 6,000 V/cm field at particle concentrations normally encountered in the experimental apparatus.

TABLE 1. SATURATION CURRENT LEVEL

Particle Diameter (μm)	Saturation Charge Level (Elem Units)	Particle Conc (#/cm³)	Flow Rate (ℓpm)	Saturation Current (amps)
2.0	701	7.1	0.24	1.9×10^{-13}
1.1	212	17.7	0.24	1.4×10^{-13}
0.5	44	35.3	0.24	5.9×10^{-14}

The actual saturation current value obtained was 2×10^{-11} amps. This measurement was made before the diffusion battery was added to the experimental apparatus and may represent the current carried by the submicron fraction of the aerosol. The saturation current level was obtained at low voltages which indicates that the majority of the charge was carried by small particles having a high electrical mobility.

A Model 3030 electrical aerosol analyzer (EAA) was modified for measuring the charge level on the particles. Before modifying the instrument, measurements of the particle charge level were not reproducible. This is believed to be the result of high particle losses within the instrument.

The EAA was modified as shown in Figure 6 with the Faraday cup remounted on the face of the instrument. The charged particles could then be collected in the Faraday cup and particle losses in the remainder of the instrument were thus avoided.

The particle charge level can be determined from the value of the current measured with the electrometer in the EAA and the number concentration as measured with the optical particle counter:

$$n_p = \frac{I}{N_o Qe} \qquad (13)$$

This method gave reproducible results after installing the diffusion battery and was used for determining the particle charge levels given in this report.

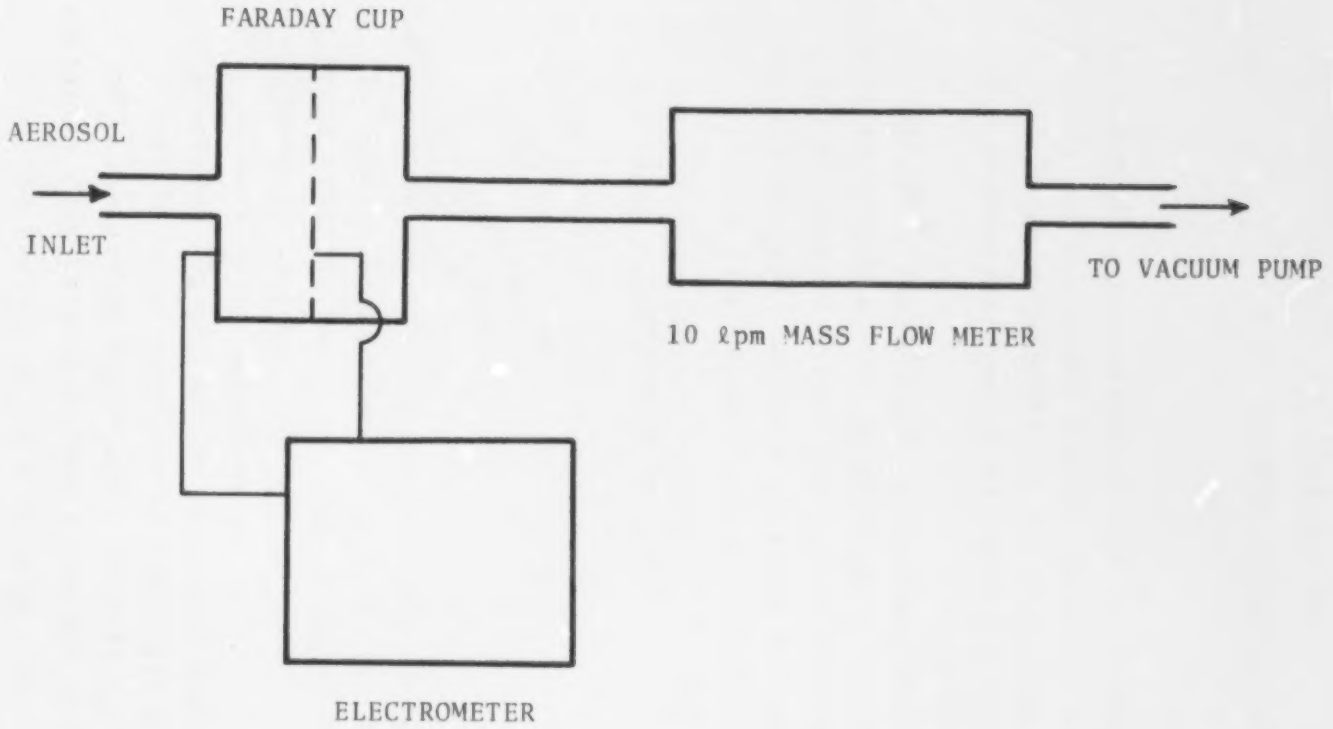

Figure 6. Modified electrical aerosol analyzer.

SECTION 4

EXPERIMENTAL RESULTS

SINGLE STAGE COLLECTION

The collection efficiency was determined as a function of the impaction parameter for both charged and uncharged aerosols. Collection of charged particles in the impactor without the impaction plate in place was found to be negligible with each of the three jet stages used.

The electrical field strength in the charger shown in Figure 3 was 7,000 V/cm. Actual charge levels on the particles were somewhat less than the saturation charge because of the short residence time in the charging section. For the PSL particles used in this study the average charge level was:

Particle Diameter (μm)	Average Charge Level (No. of elementary units)
2.0	322
1.0	201
0.5	53

Sixth Stage Results

Figures 7 through 12 are the results obtained with 0.5 μm diameter PSL particles and the various substrates. These are similar to the results obtained with the other particle sizes. In all cases collection efficiencies were found to be greater for the charged particles than the uncharged particles.

Impaction of charged particles on the greased substrates was only slightly more efficient for a given value of the impaction parameter, K_p, than with uncharged particles. The effect was more dramatic for the other substrates with efficiency being as much as 20 percent greater for the charged particles for a given K_p value.

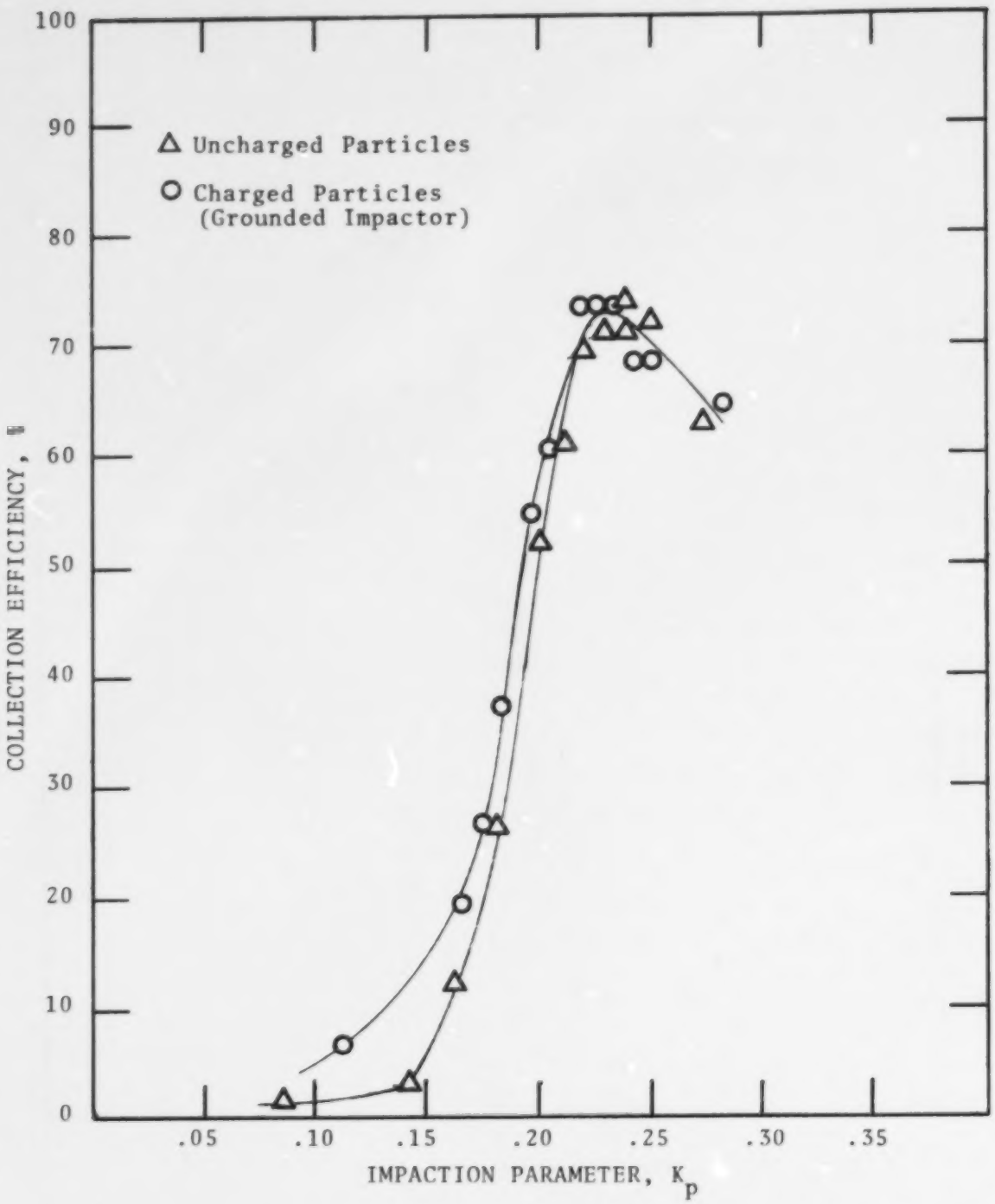

Figure 7. Impaction characteristics with greased plate (0.5 μm dia. PSL).

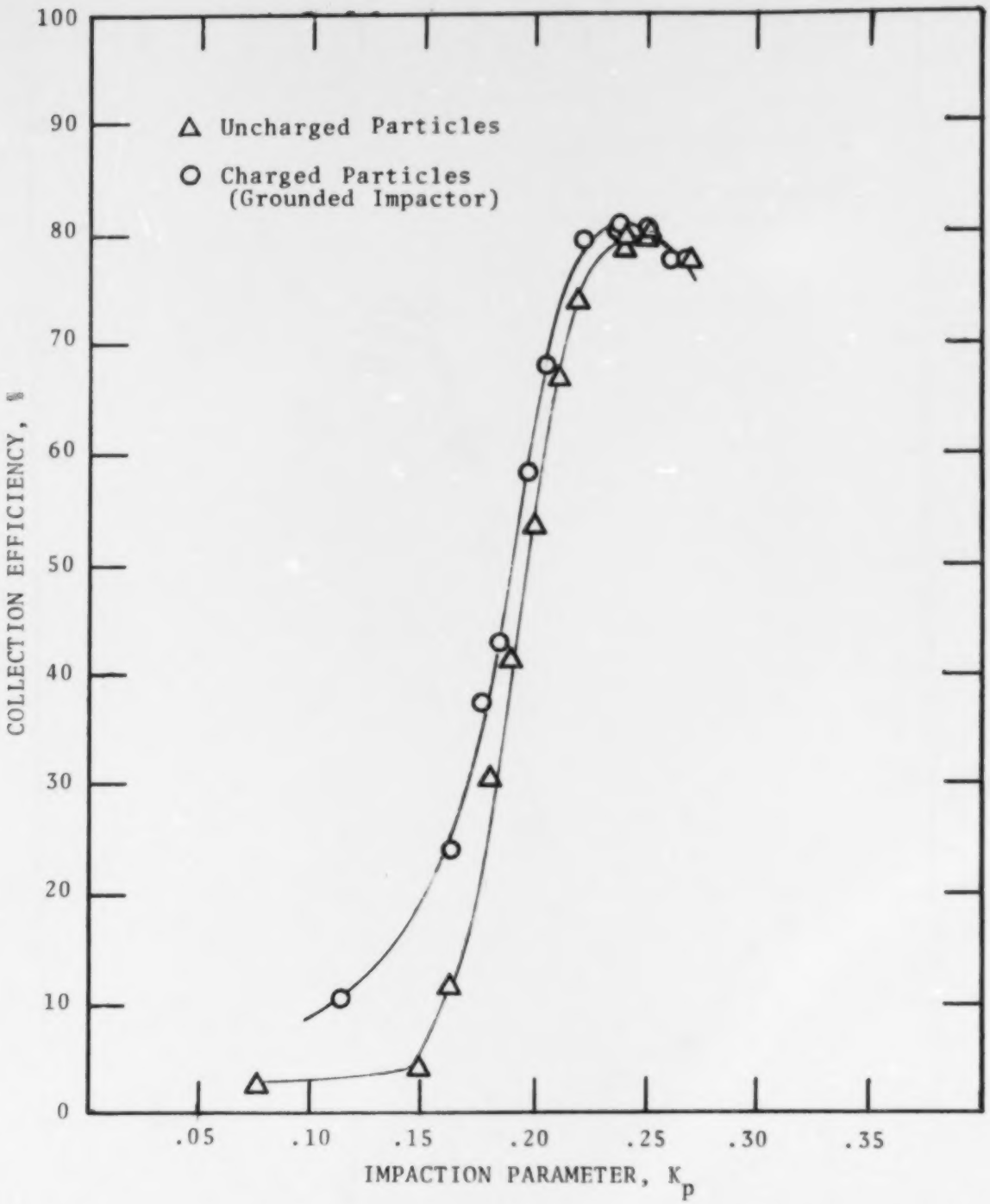

Figure 8. Impaction characteristics with greased foil (0.5 μm dia. PSL).

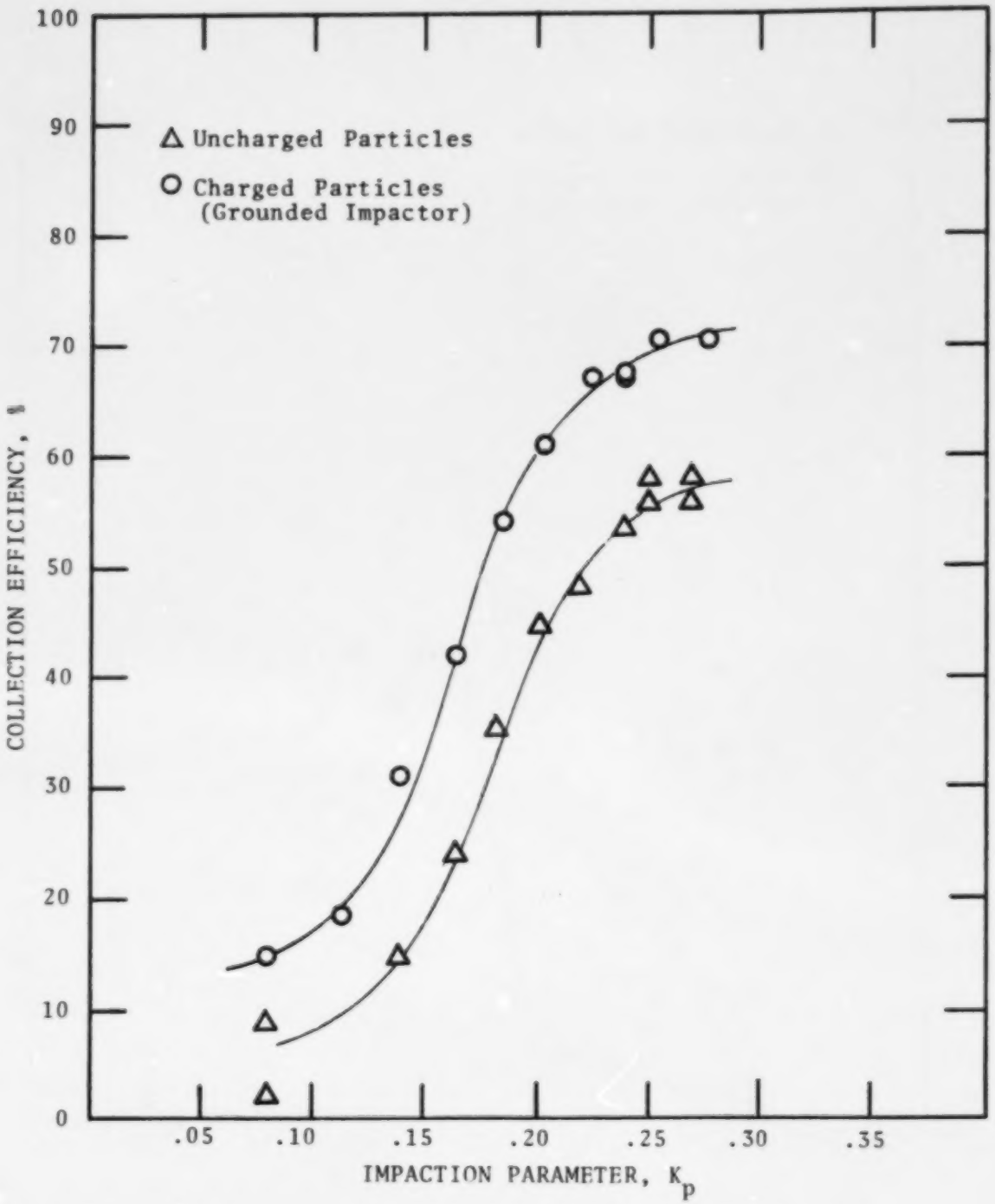

Figure 9. Impaction characteristics with glass fiber filter (0.5 μm dia. PSL).

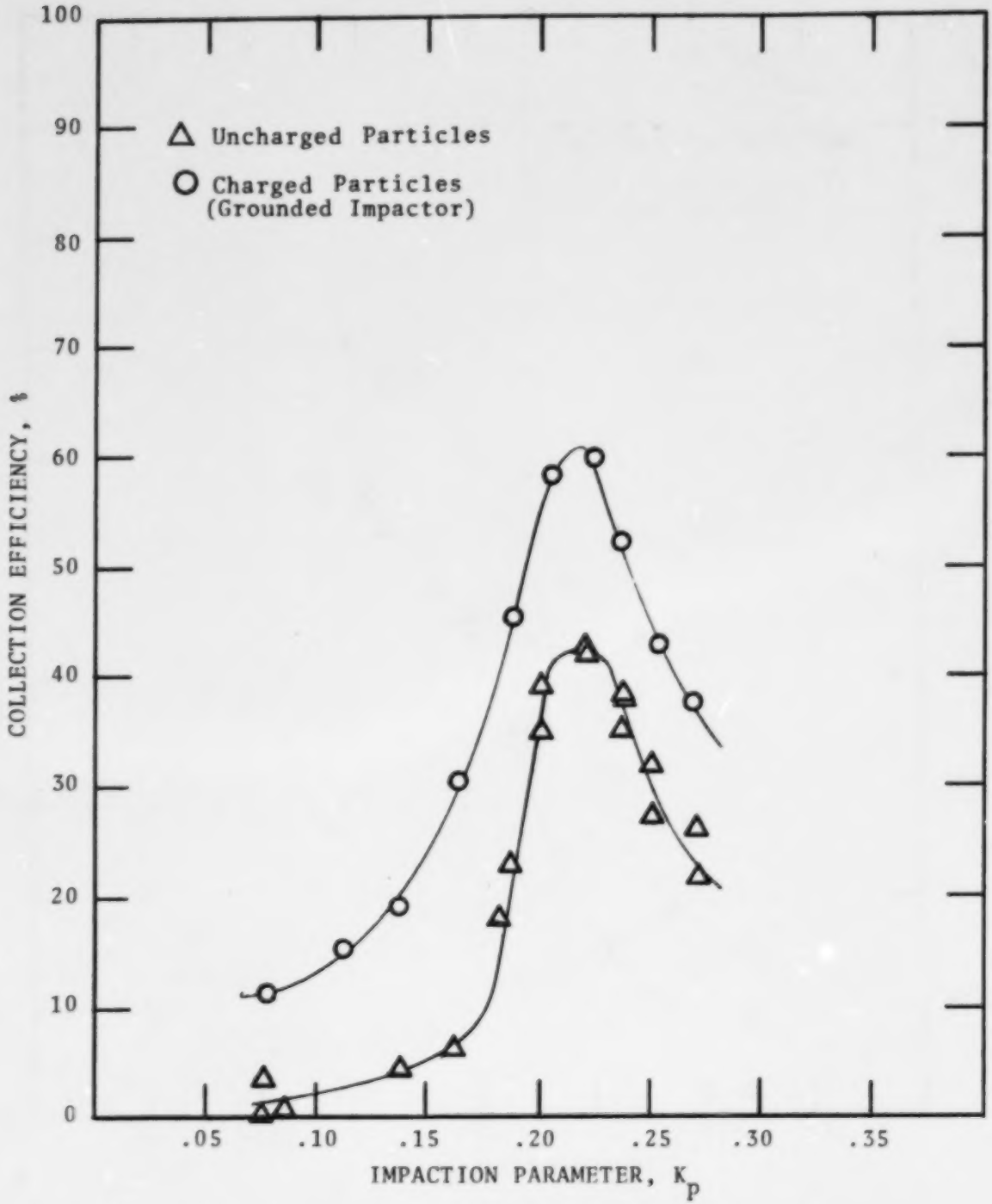

Figure 10. Impaction characteristics with ungreased plate (0.5 μm dia. PSL).

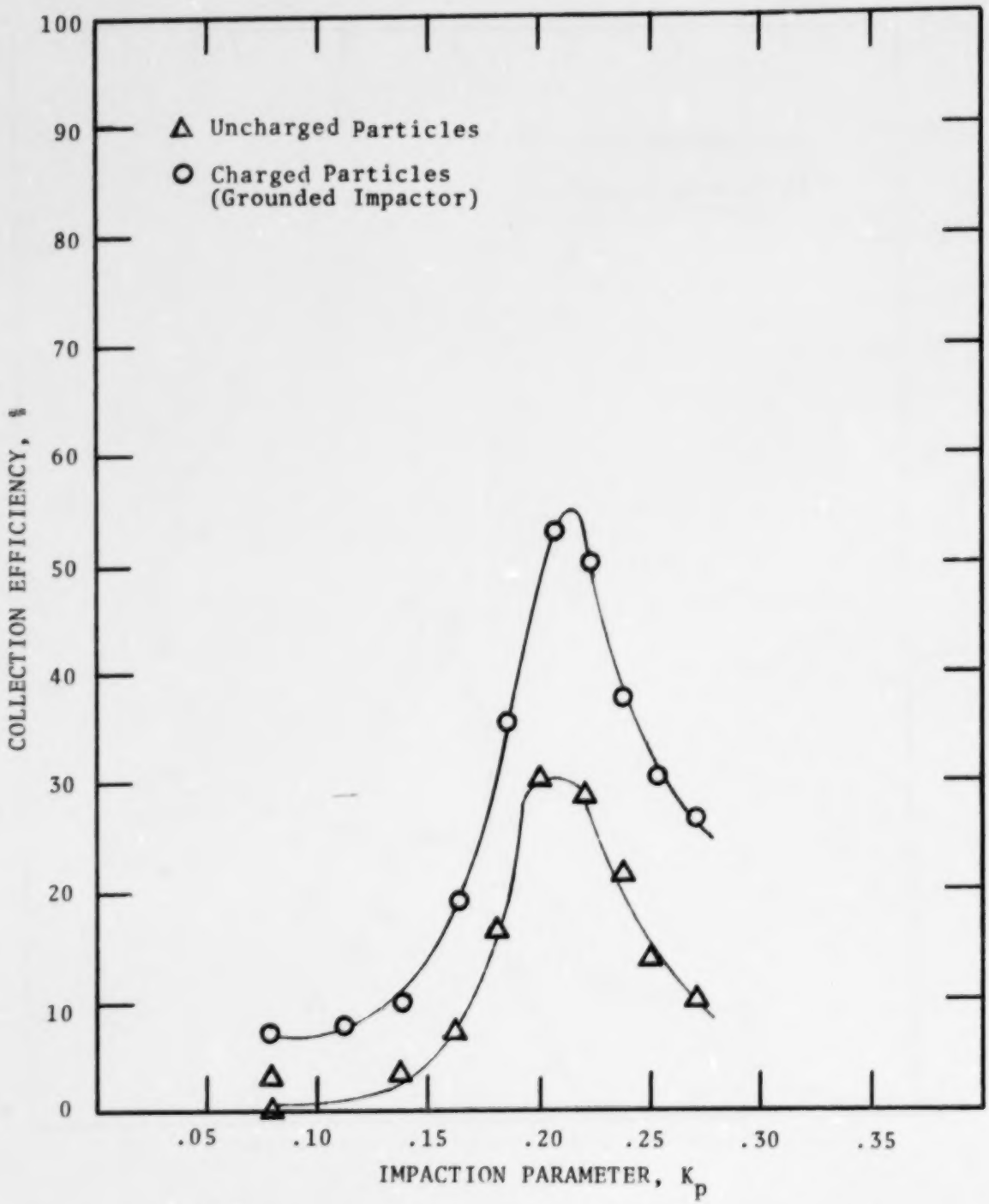

Figure 11. Impaction characteristics with ungreased foil (0.5 μm dia. PSL).

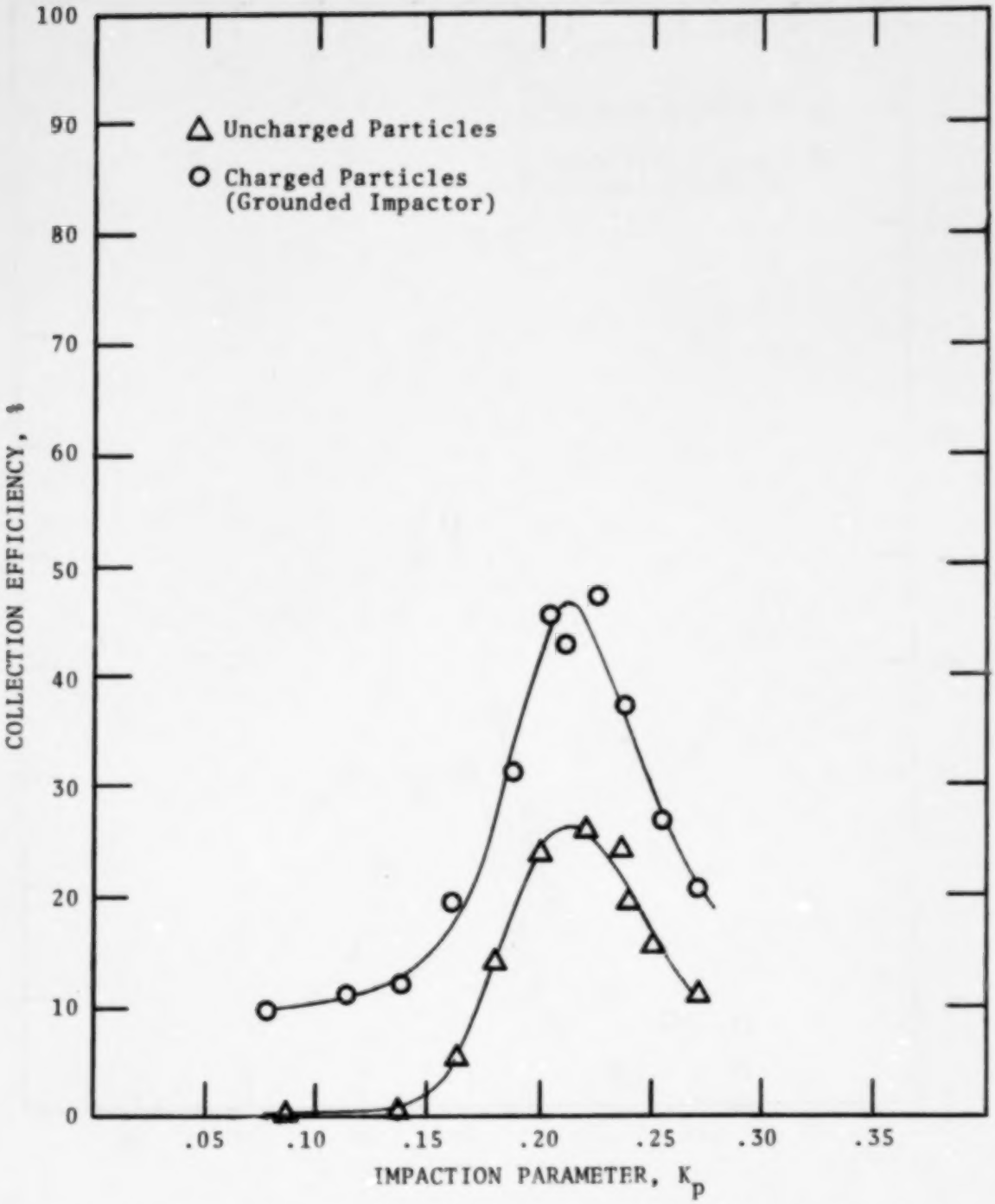

Figure 12. Impaction characteristics with Mylar substrate (0.5 μm dia. PSL).

The impaction efficiency was less than 100% for the PSL particles and all the substrates tested because of particle bounce. This result is similar to that found by Rao (1975). The maximum obtainable impaction efficiency was increased by as much as 20% for substrates other then the greased impaction substrates.

Stage Five Results

Figures 13 through 17 are the results obtained with the 1.1 μm diameter PSL particles and the various substrates. Collection of charged particles on the greased plate leveled off to an overall efficiency of 15 to 20% for low values of the impaction parameter, K_p. This is a somewhat greater efficiency than the results obtained with the 0.5 μm diameter PSL.

Figure 16 shows that collection of uncharged particles on ungreased plate was greater than for charged particles. It is believed that the impactor was not grounded during this run.

Stage Four Results

Figures 18 through 23 are the results obtained with the 2.0 μm diameter PSL particles and the various substrates. These results are similar to those obtained with the 0.5 μm diameter PSL particles on the 6th stage.

Tables 2 through 4 give the value of $K_{p_{50}}$ and the maximum impaction efficiency for the three particle sizes tested.

The change in the impaction parameter, $K_{p_{50}}$, amounted to approximately 10% for most substrates. The effect of particle mobility was insignificant as the change in $K_{p_{50}}$ was similar for each of the PSL particle sizes tested.

MULTIPLE STAGE COLLECTION

Collection efficiencies were determined as a function of the impaction parameter for both charged and uncharged aerosols. Stages 1 through 6 were installed in the cascade impactor for these tests. The electrical field strength in the charger shown in Figure 3 was 7,000 V/cm.

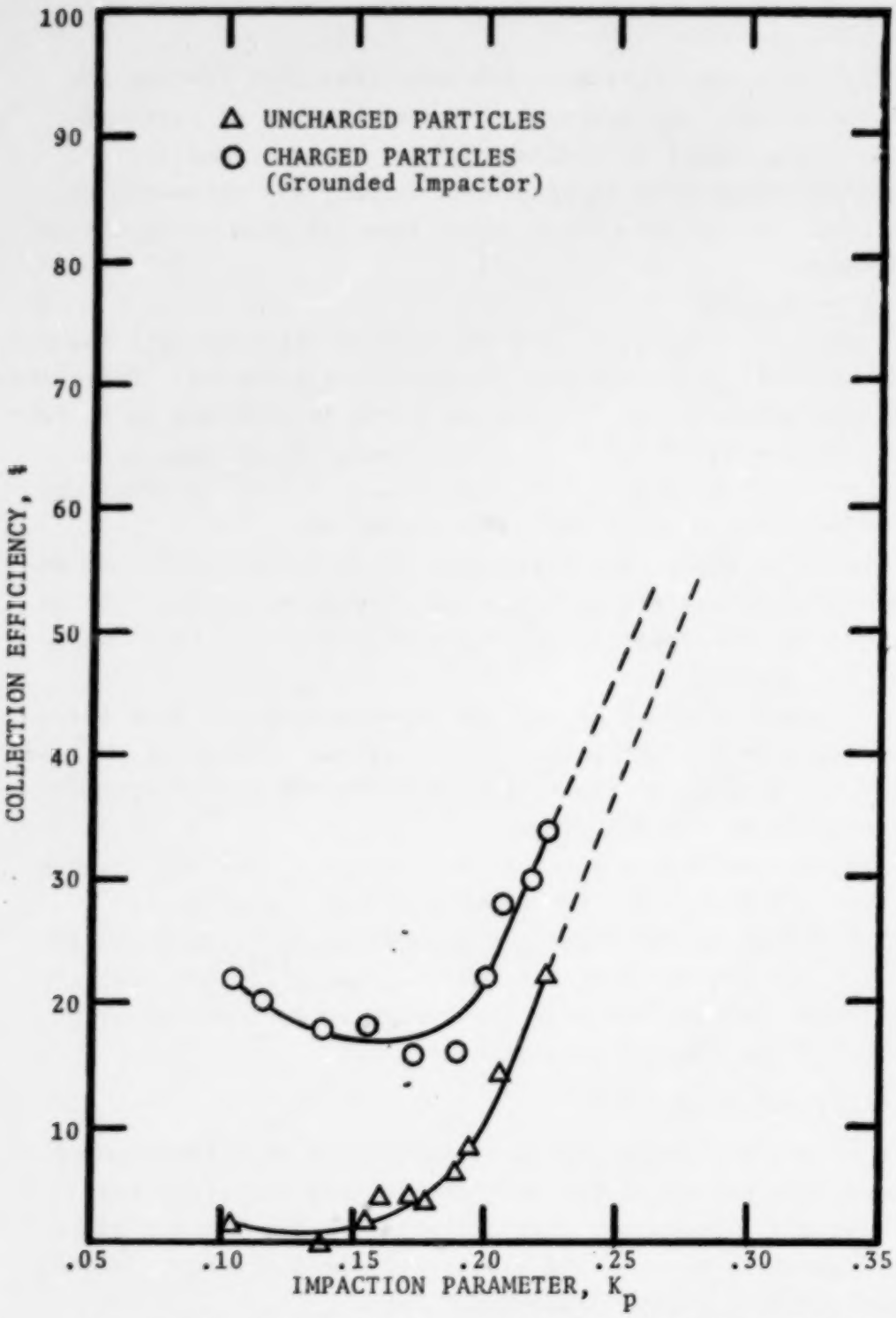

Figure 13. Stage 5 impaction characteristics of greased plate (1.1 μm dia. PSL).

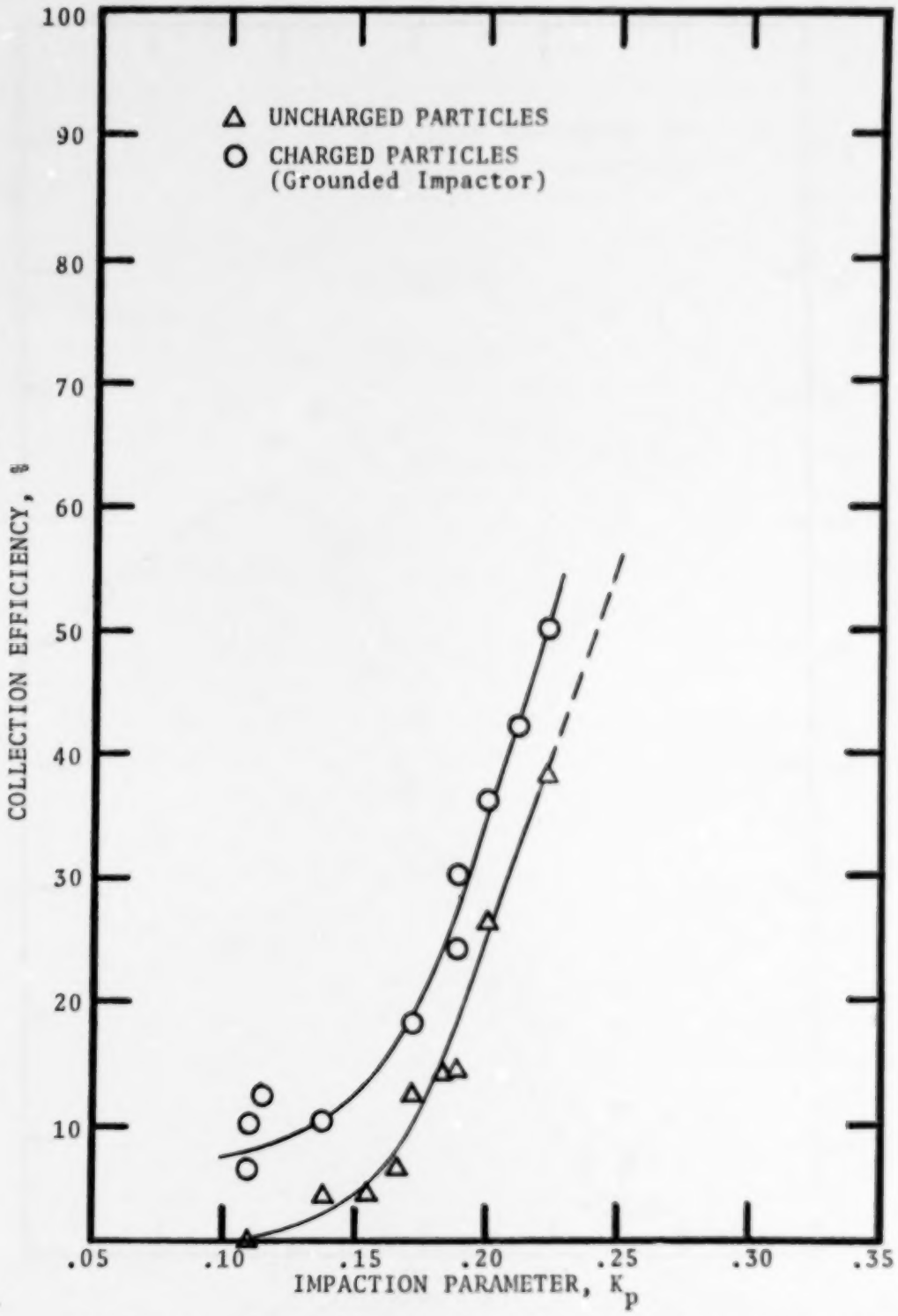

Figure 14. Stage 5 impaction characteristics of greased foil (1.1 μm dia. PSL).

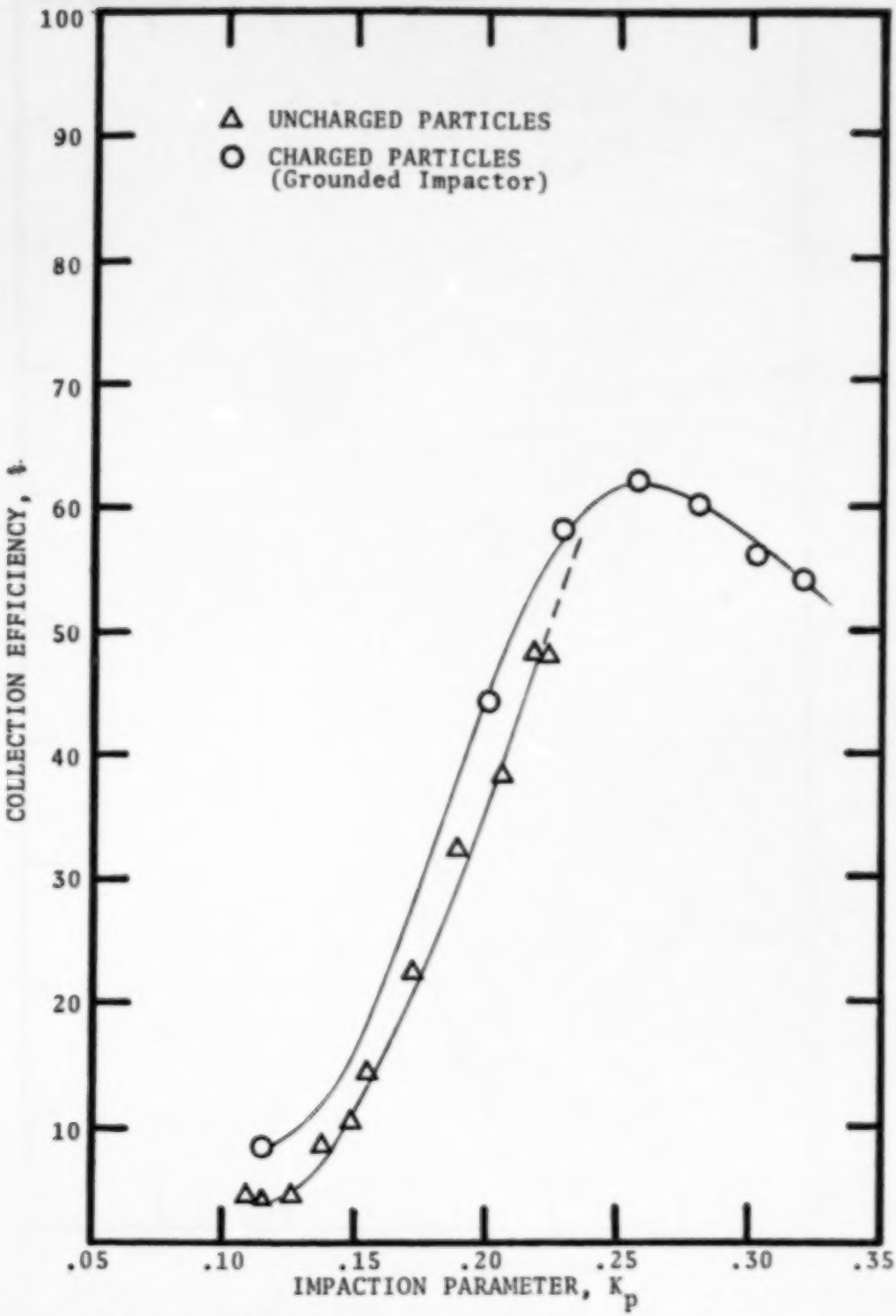

Figure 15. Stage 5 impaction characteristics of glass fiber filter (1.1 μm dia. PSL).

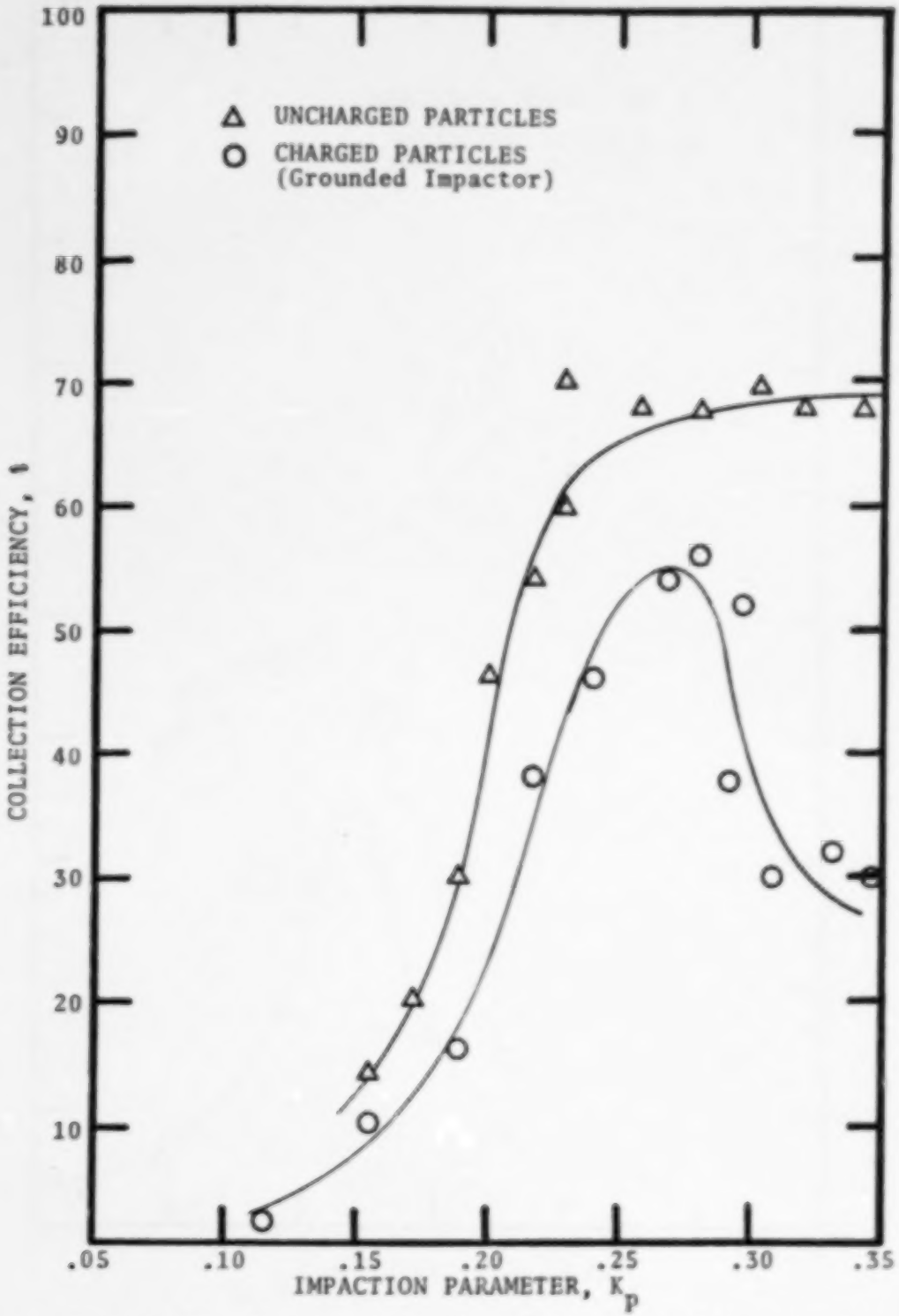

Figure 16. Stage 5 impaction characteristics on ungreased plate (1.1 μm dia. PSL).

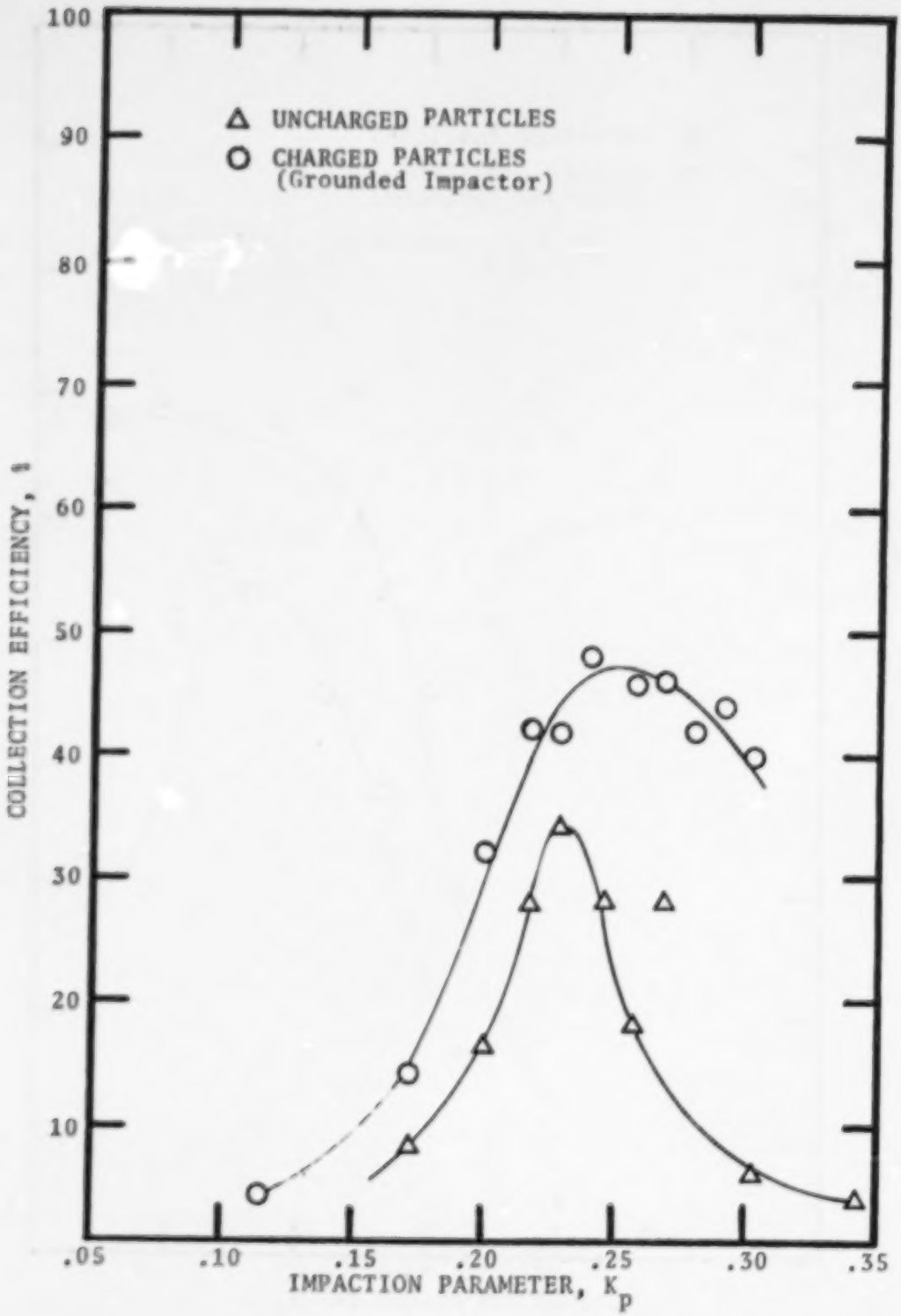

Figure 17. Stage 5 impaction characteristics of ungreased foil (1.1 μm dia. PSL).

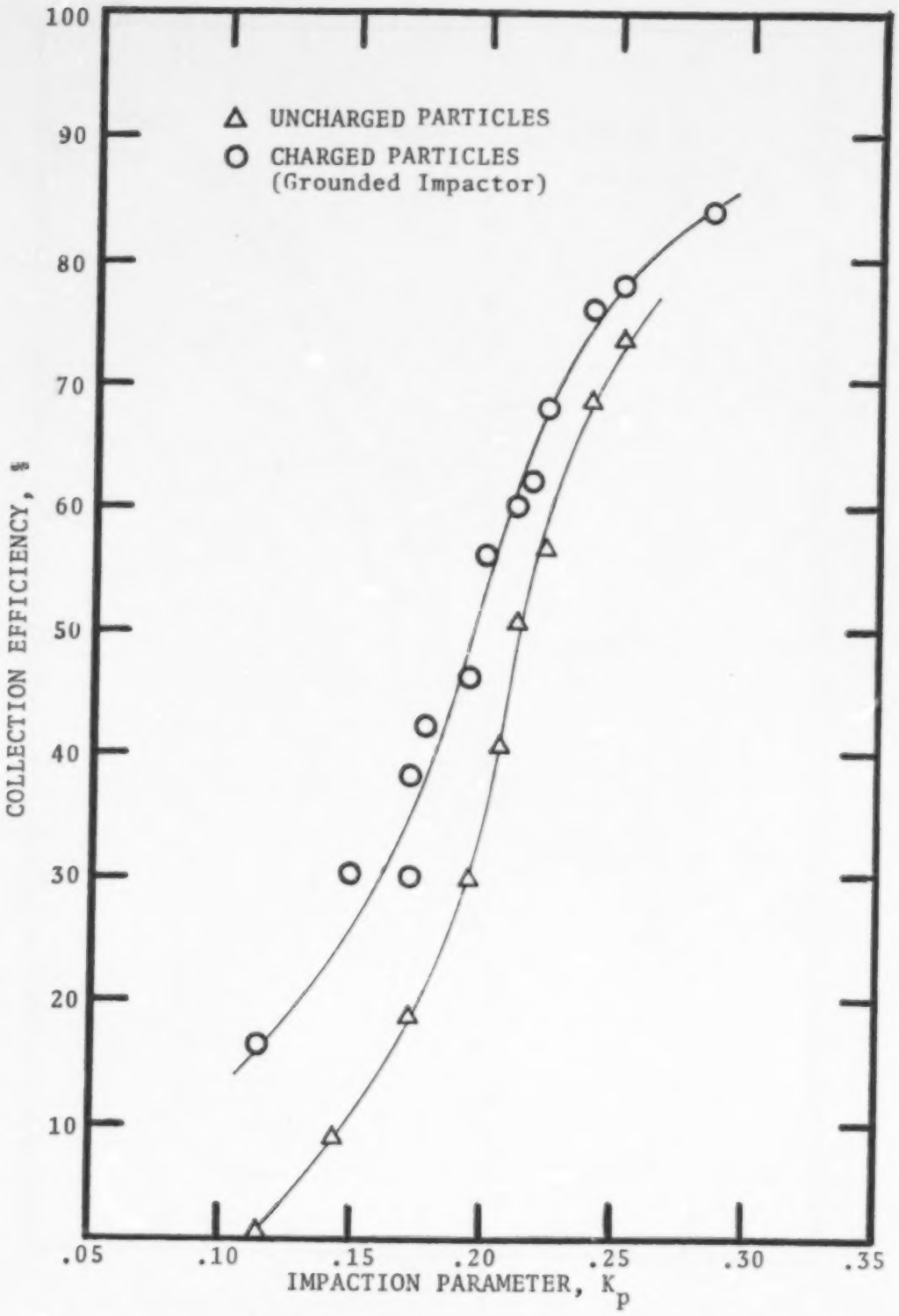

Figure 18. Stage 4 impaction characteristics of greased plate (2.0 μm dia. PSL).

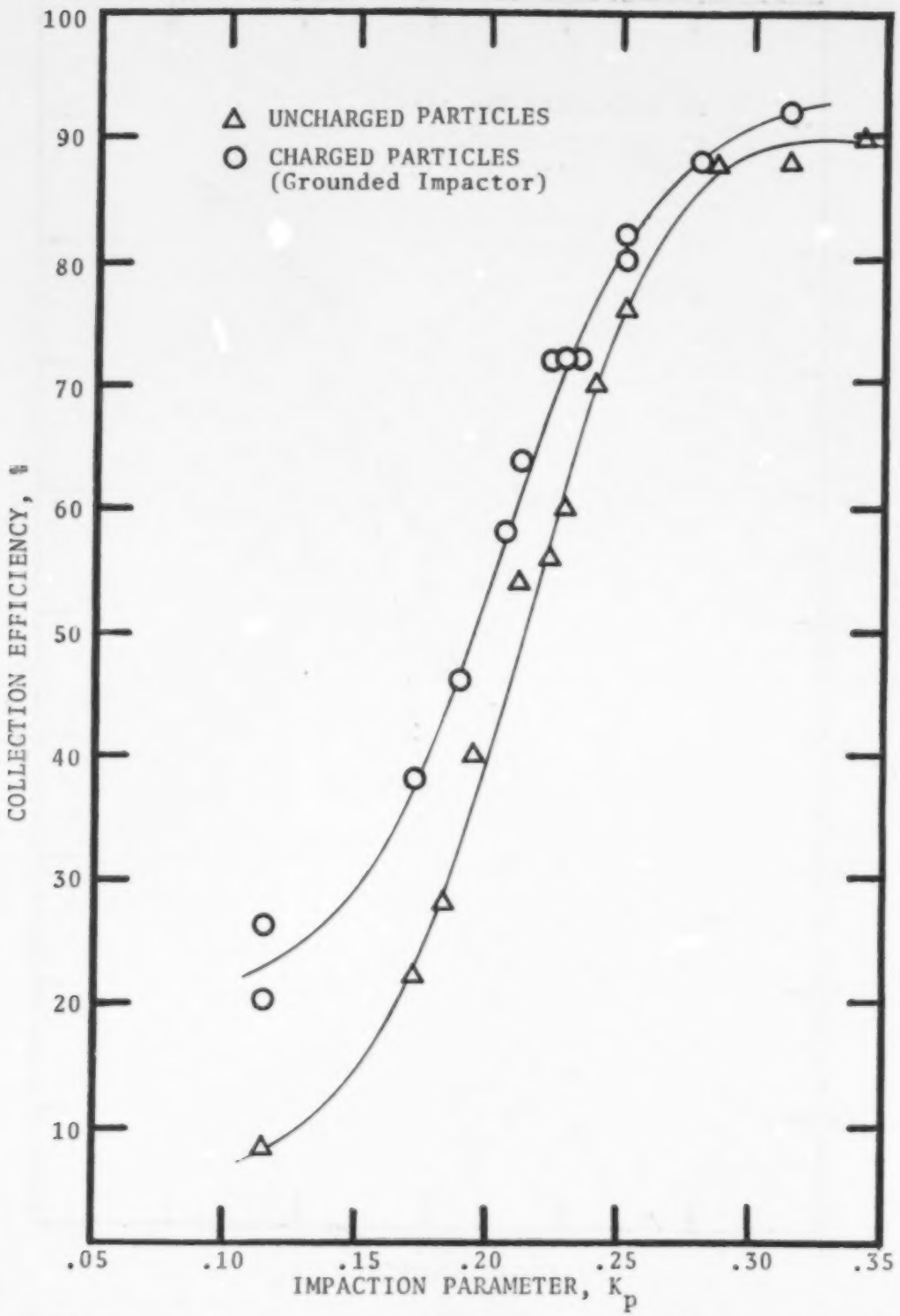

Figure 19. Stage 4 impaction characteristics of greased foil (2.0 μm dia. PSL).

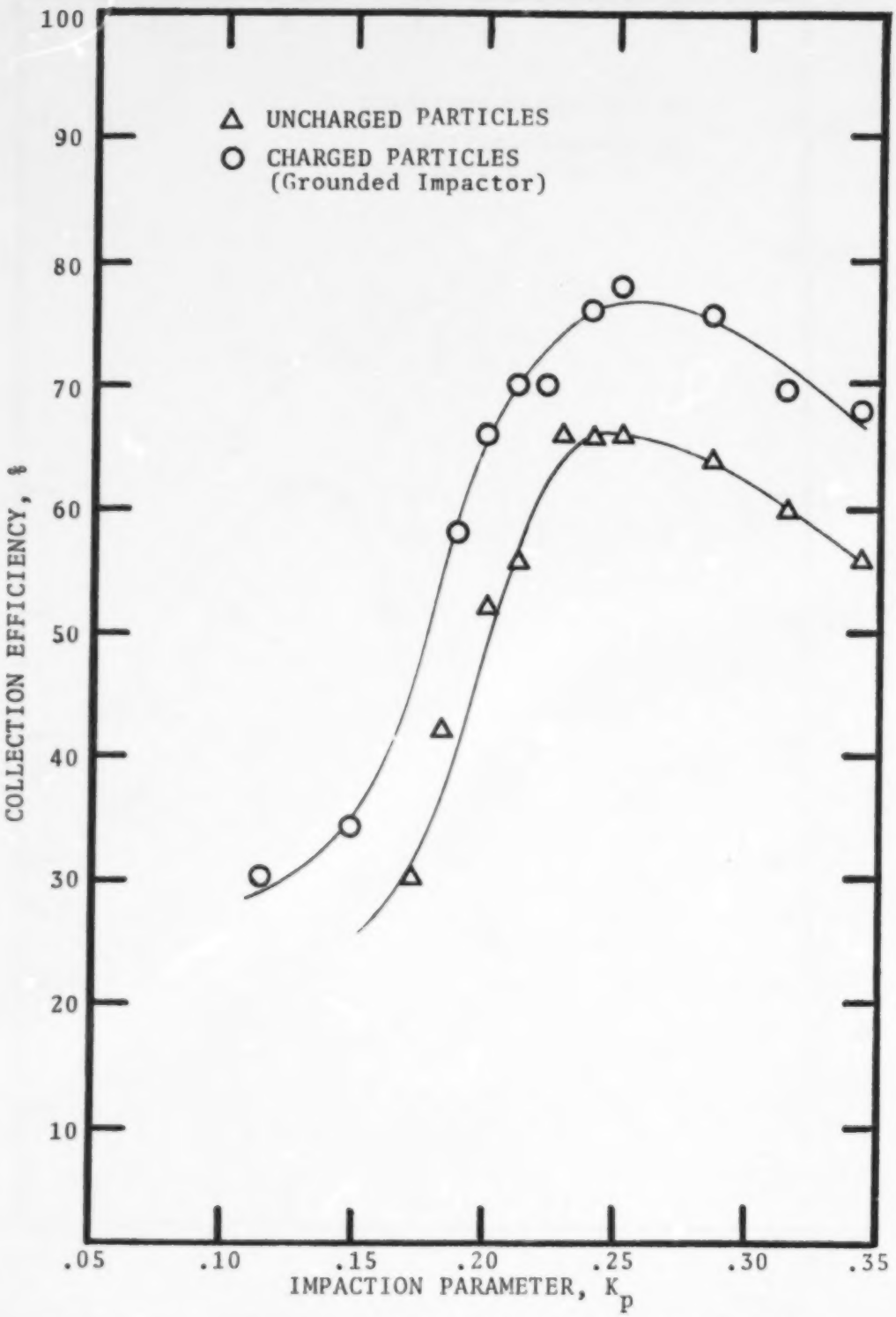

Figure 20. Stage 4 impaction characteristics of glass fiber filter (2.0 μm dia. PSL).

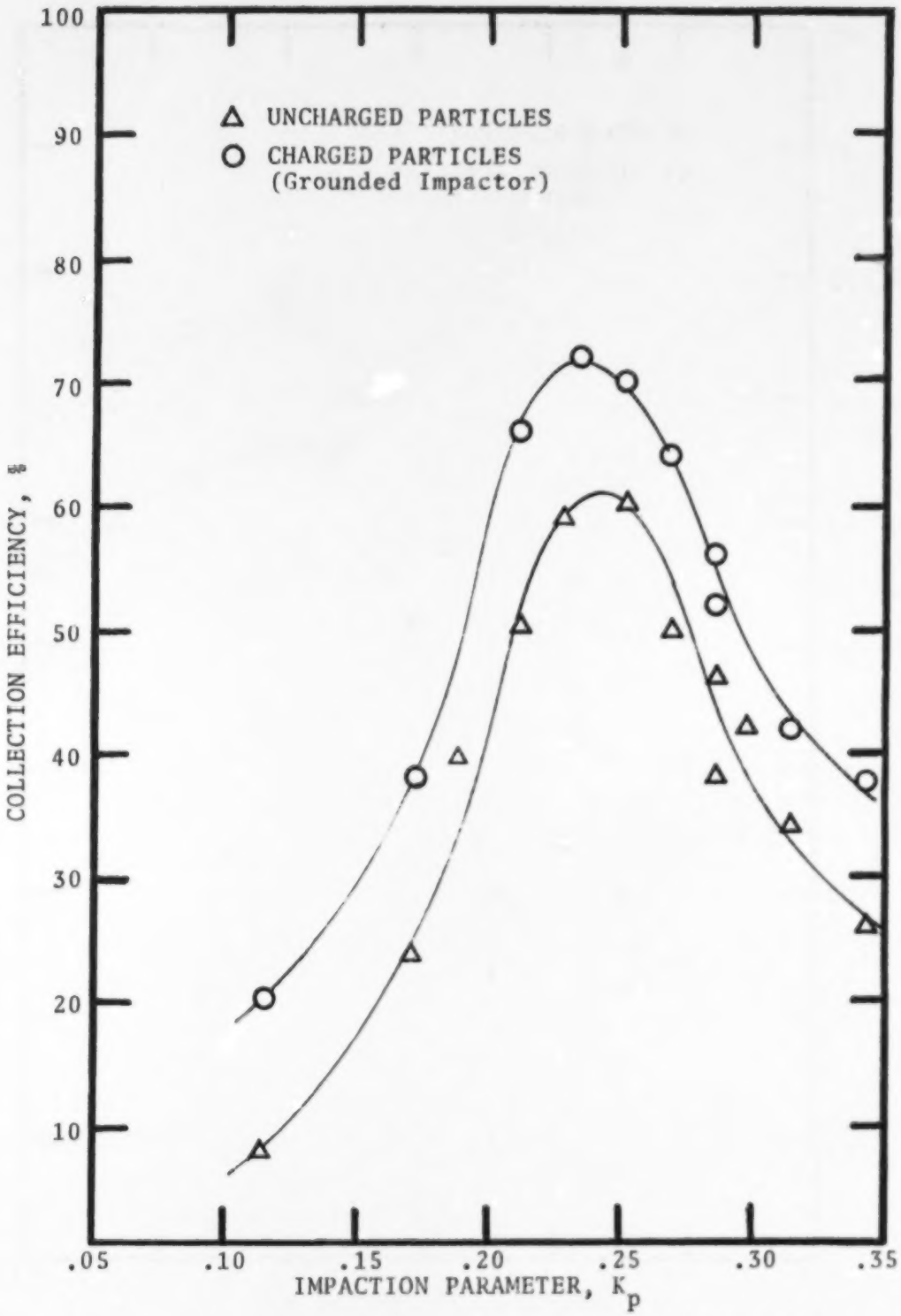

Figure 21. Stage 4 impaction characteristics of ungreased plate (2.0 μm dia. PSL).

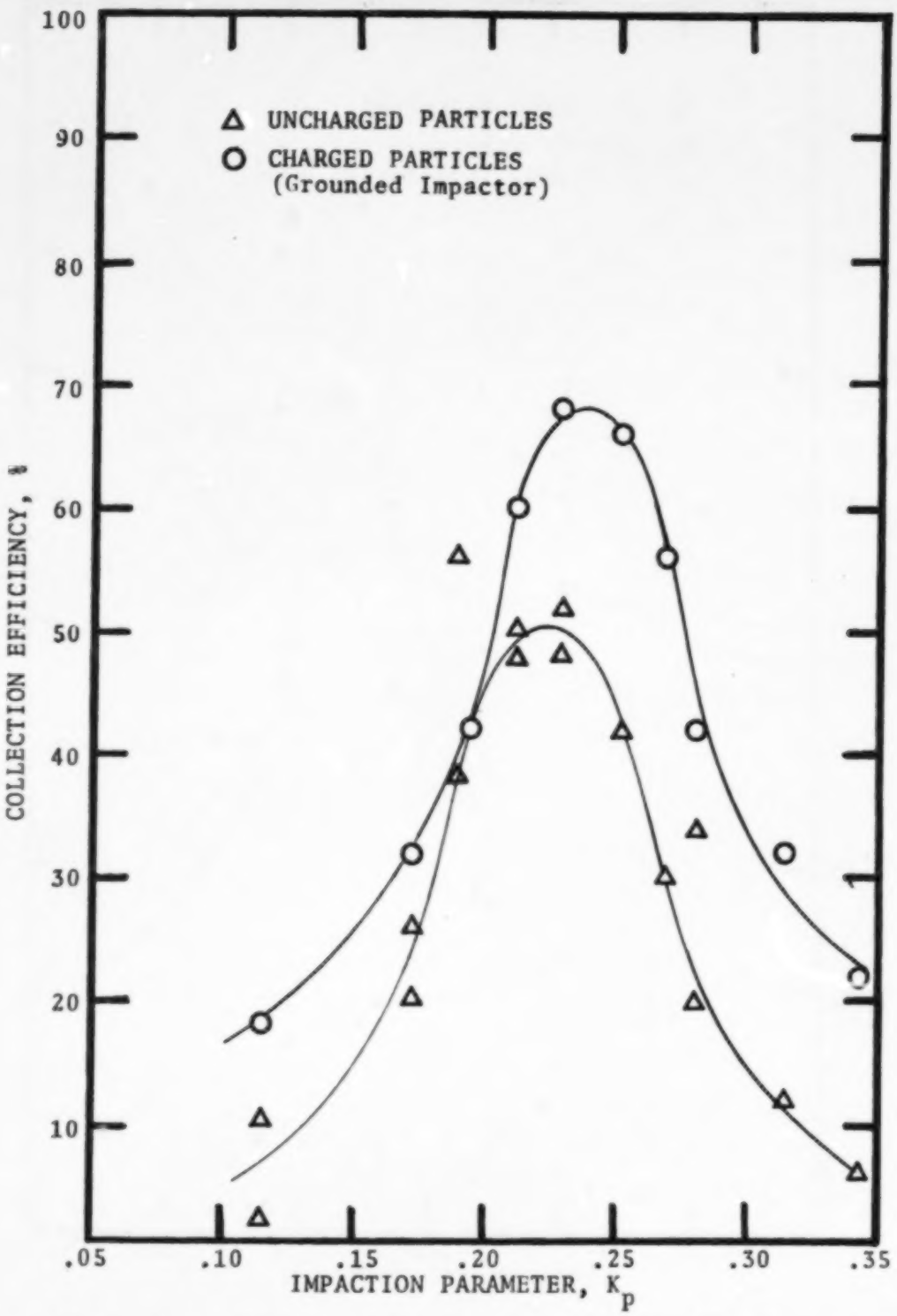

Figure 22. Stage 4 impaction characteristics of ungreased foil (2.0 μm dia. PSL).

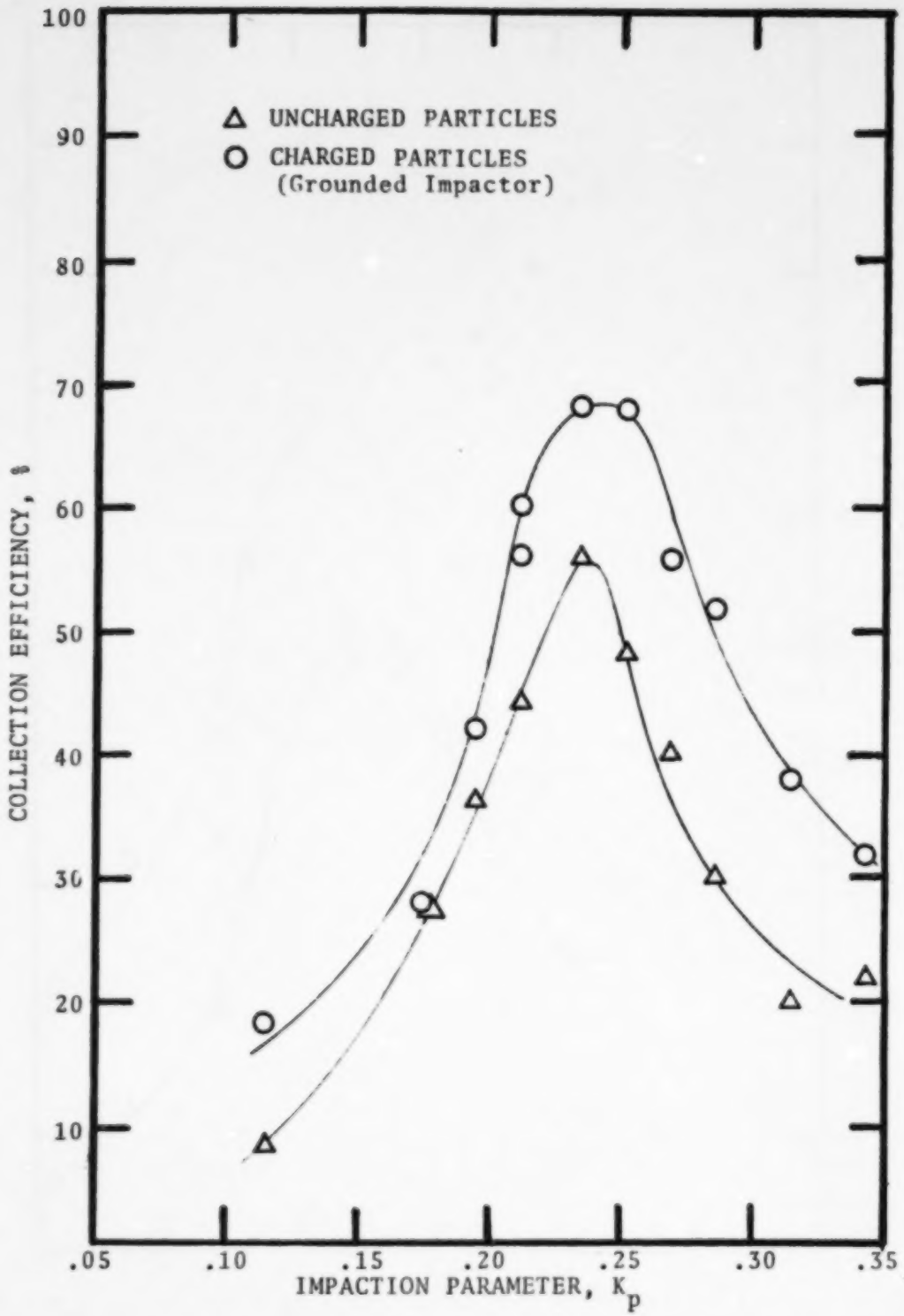

Figure 23. Stage 4 impaction characteristics of Mylar film (2.0 μm dia. PSL).

TABLE 2. IMPACTION CHARACTERISTICS FOR VARIOUS SUBSTRATES (0.5 μm dia. PSL)

	$K_{p_{50}}$		Maximum Collection Efficiency, %	
Substrate	Charged	Uncharged	Charged	Uncharged
Greased Plate	0.19	0.20	74	74
Greased Foil	0.19	0.20	80	80
Glass Fiber Filter	0.18	0.21	70	58
Ungreased Plate	0.19	0.22(1)	60	42
Ungreased Foil	0.20	0.22	53	30
Mylar	0.21(1)	0.22(1)	48	27

TABLE 3. IMPACTION CHARACTERISTICS FOR VARIOUS SUBSTRATES (1.1 μm dia. PSL)

	$K_{p_{50}}$		Maximum Collection Efficiency, %	
Substrate	Charged	Uncharged	Charged	Uncharged
Greased Plate	0.25	0.27	--	--
Greased Foil	0.22	0.24	--	--
Glass Fiber Filter	0.21	0.22	63	--
Ungreased Plate	0.21	0.24	70	55
Ungreased Foil	0.23(1)	0.24(1)	47	35

(1) Estimated by extrapolating the portion of the curve having a strong, positive slope.

TABLE 4. IMPACTION CHARACTERISTICS FOR VARIOUS SUBSTRATES (2.02 μm dia. PSL)

Substrate	K_{p50}		Maximum Collection Efficiency %	
	Charged	Uncharged	Charged	Uncharged
Greased Plate	0.20	0.22	90	90
Greased Foil	0.19	0.22	90	90
Glass Fiber Filter	0.18	0.20	78	66
Ungreased Plate	0.19	0.21	72	61
Ungreased Foil	0.20	0.21	68	51
Mylar Film	0.20	0.22	68	56

Figure 24 shows the results with a greased Mylar substrate. This figure is similar to Figures 7, 8, 13, 14, 18, and 19 which are for collection on various greased substrates with only one impaction stage. The collection efficiency for a given flow rate is somewhat greater in Figure 24 than is shown in the other figures. This increased collection efficiency may be attributed to particle collection on the upper stages of the cascade impactor.

The collection characteristics for glass fiber filters is shown in Figure 25. This figure is similar to Figures 9, 15, and 20 which were obtained with single stages. This indicates that collection of charged particles with glass fiber filters is minimal on the upper stages.

An ungreased plate was used as the collection substrate for the data shown in Figure 26. The curves for charged and uncharged particles are quite similar to the ones found in Figures 10, 11, 16, 17, 21, and 22 for other ungreased substrates. Again this indicates that the collection of the charged particles on the upper stages of the cascade impactor is minimal.

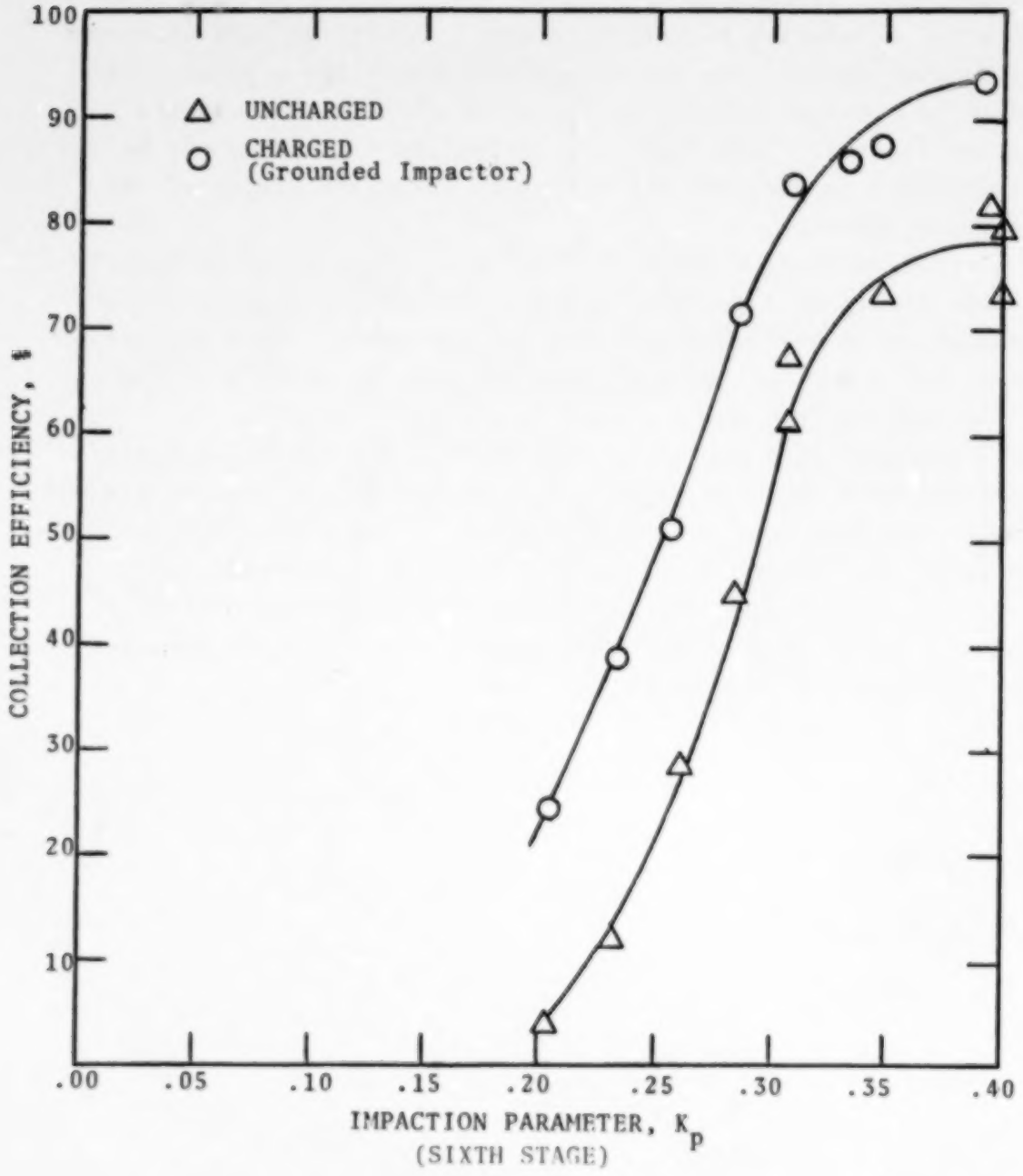

Figure 24. Collection characteristics of greased Mylar substrates with stages 1 through 6 installed (0.76 μm dia. PSL).

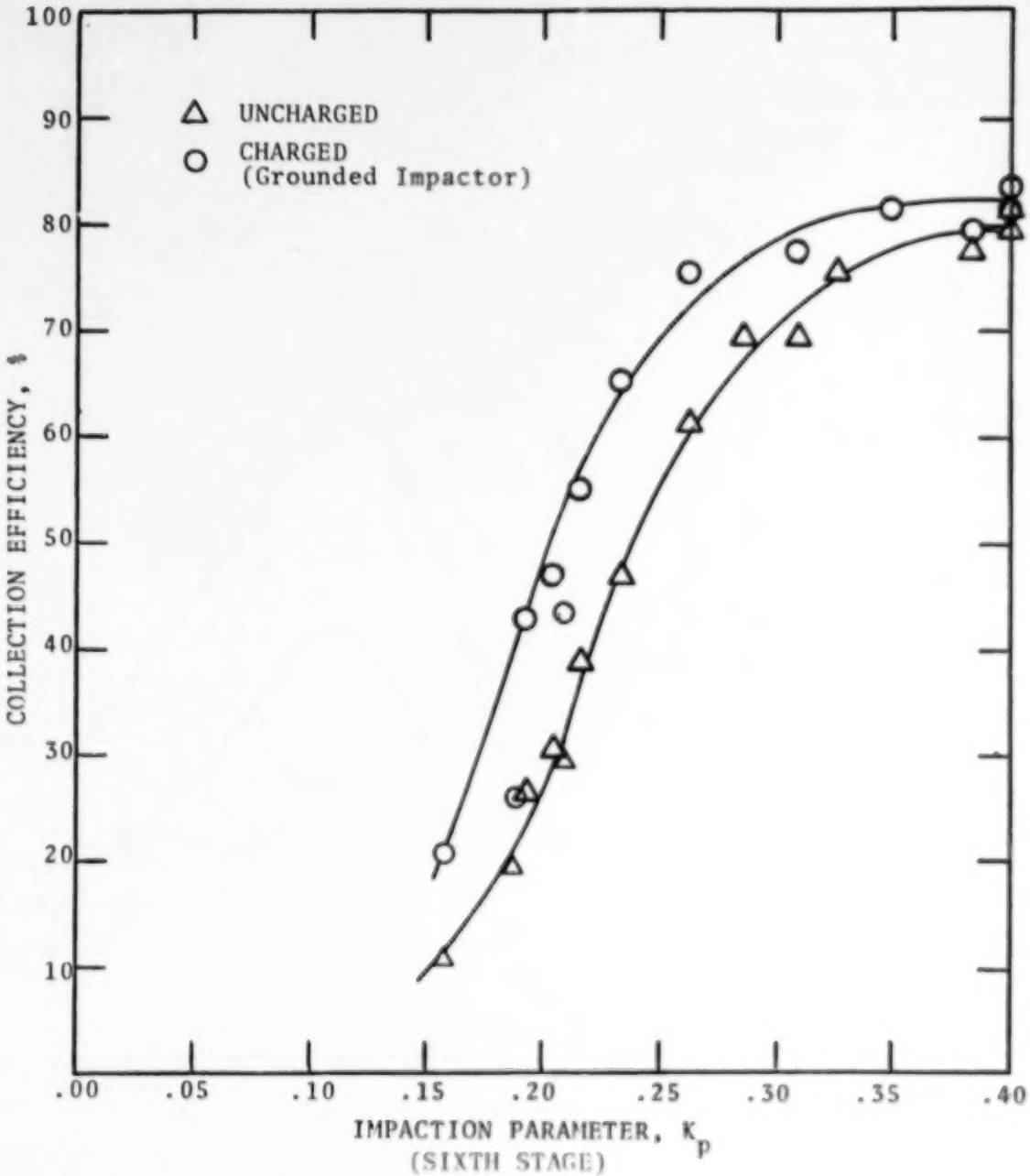

Figure 25. Collection characteristics of glass fiber filter substrates with stages 1 through 6 installed (0.76 μm dia. PSL).

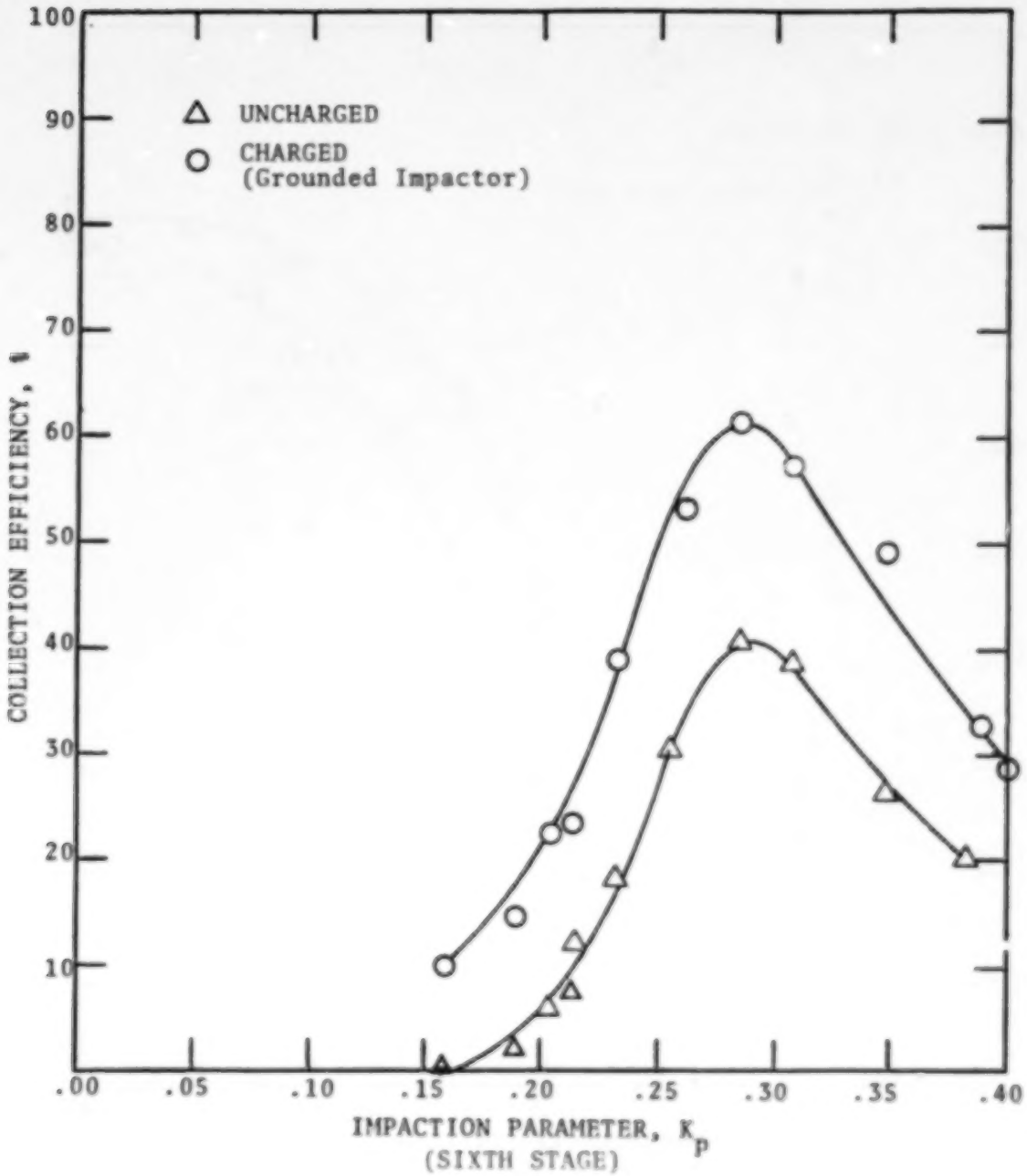

Figure 26. Collection characteristics for an ungreased impaction plate with stages 1 through 6 installed (0.76 μm dia. PSL).

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